Neutrino Experiments

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Weak Interactions and Neutrinos
Δελφοι, 6 June 2005

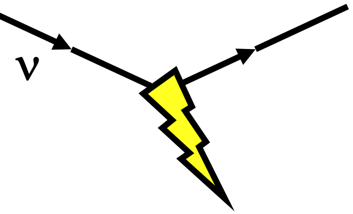
Neutrinos: View from the Center of the Earth

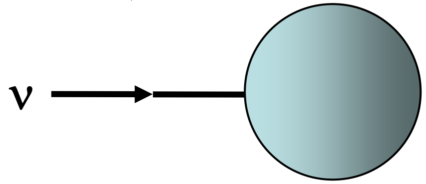
- Today we'll choose a broad overview
  - rather than a focused study in depth
  - *neutrino people: this is for the energy frontier folks. please be patient! you'll get your turn later in the week*

clever photos courtesy Symmetry magazine

The Broadest Goals

- Understand mixing of neutrinos
  - a non-mixing? CP violation?
- Understand neutrino mass
  - absolute scale and hierarchy
- Understand ν interactions
  - new physics? new properties?
- Use neutrinos as probes
  - nucleon, earth, sun*, supernovae*





** fascinating topics, but outside the scope of this talk. See Dave Wark…*

Neutrino Mass Eigenstates

- The building blocks of what we know
  - #νs with weak couplings:
    - W^+: 3 observed (DONUT)
    - Z^0: exactly 3 (LEP, SLD)
  - Solar neutrino oscillation: …, SNO, KAMLAND
  - Atmospheric neutrinos: …, Super-K, K2K
  - Puzzles and null results: LSND, CHOOZ
    - LSND "puzzle" is requirement of more neutrinos
    - CHOOZ/Palo Verde suggest one small mixing

Qualitative Questions

- The questions facing us now are fundamental, and not simply a matter of "measuring oscillations better"
- Examples:
  - Are there more than three neutrinos?
  - What is the hierarchy of masses?
  - Can neutrinos contribute significantly to the mass of the universe?
  - Is there CP violation in neutrino mixings?

The Broadest Goals

- Understand mixing of neutrinos
  - a non-mixing? CP violation?

- Understand neutrino mass
  - absolute scale and hierarchy

- Understand ν interactions
  - new physics? new properties?

- Use neutrinos as probes
  - nucleon, earth, etc.

What We Hope to Learn From Neutrino Oscillations

- Near future
  - validation of three generation picture
    - confirm or disprove LSND oscillations
    - precision tests of “atmospheric” mixing at accelerators
- Farther Future
  - neutrino mass hierarchy, CP violation?
    - Precision at reactors
    - sub → multi MegaWatt sources
    - 10 → 100 → 1000 kTon detectors

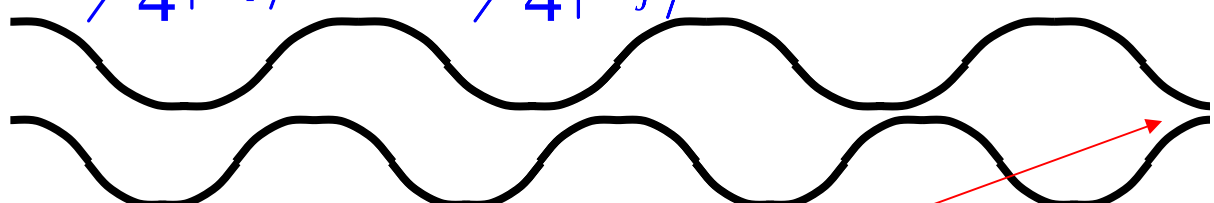
Minimal Oscillation Formalism

- If neutrino mass eigenstates: ν_1, ν_2, ν_3, etc.
- … are not flavor eigenstates: ν_e, ν_μ, ν_τ
- … then one has, e.g.,

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

take only two generations for now!

$$|\nu_\alpha\rangle = \cos\pi/4\,|\nu_i\rangle + \sin\pi/4\,|\nu_j\rangle$$



different masses alter time evolution

time

$$|\nu_\beta\rangle = -\sin\pi/4\,|\nu_i\rangle + \cos\pi/4\,|\nu_j\rangle$$

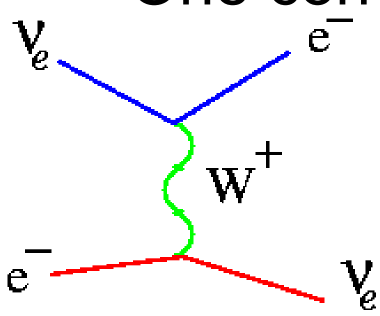
Oscillation Formalism (cont'd)

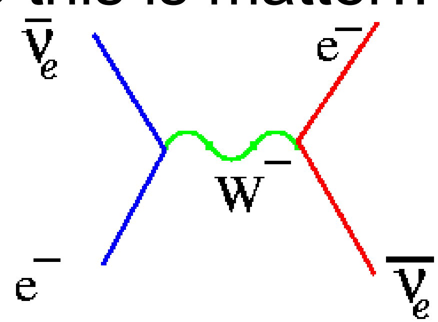
- So, still for two generations…

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

appropriate units give the usual numerical factor **1.27 GeV/km-eV²**

- Oscillations require mass differences
- Oscillation parameters are mass-squared differences, δm^2, and mixing angles, θ.
- One correction to this is matter… changes θ, L dep.





Coherent Elastic Scattering: ν_e $\bar{\nu}_e$ only!

Wolfenstein, PRD (1978)

$$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

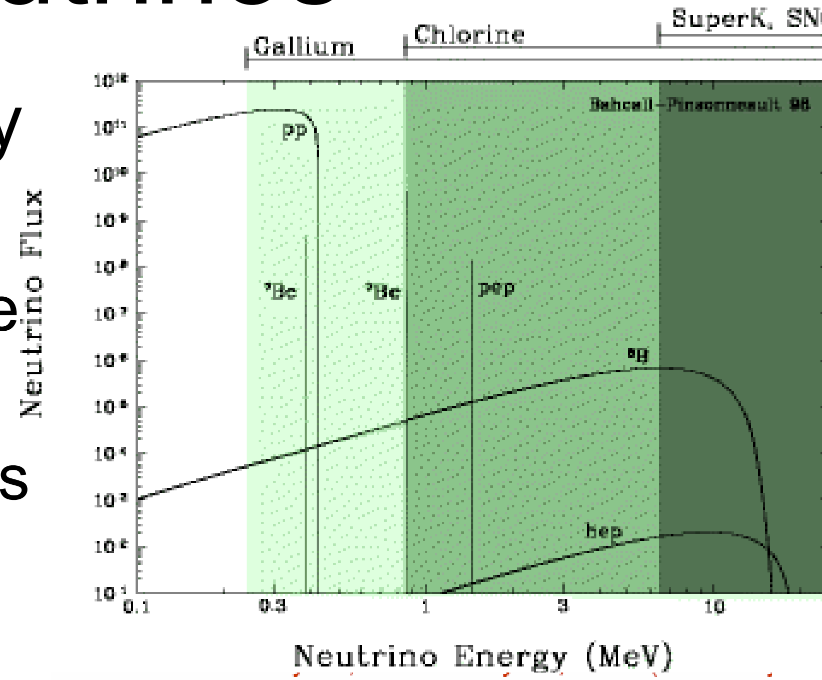
$$L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

$$x = \frac{2\sqrt{2} G_F n_e E_\upsilon}{\Delta m^2}$$

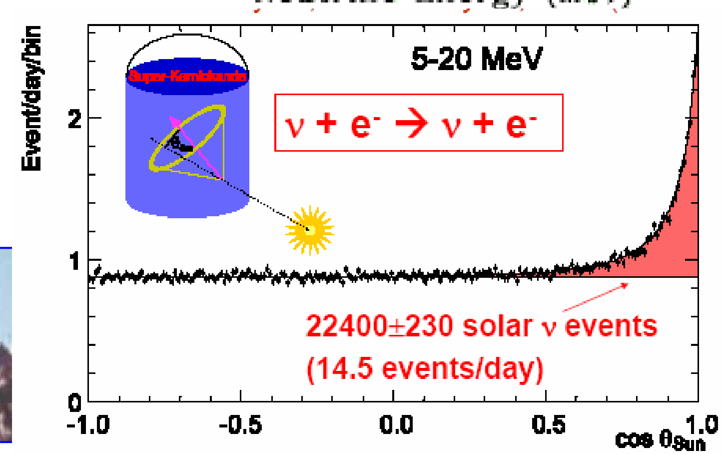
$n =$ e⁻ density

Solar Neutrinos

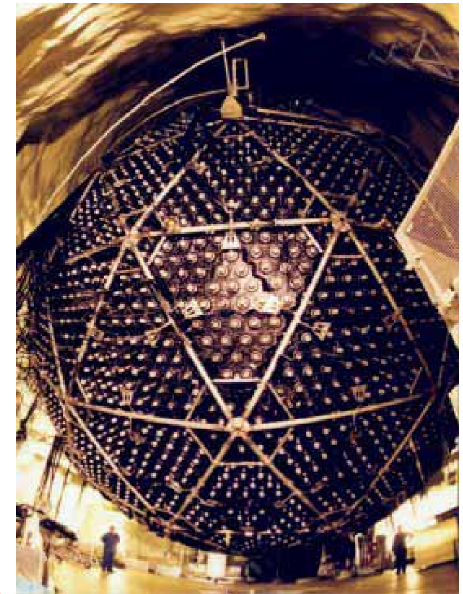
- There is a glorious history of solar neutrino physics
  - original goals: demonstrate fusion in the sun
  - first evidence of oscillations



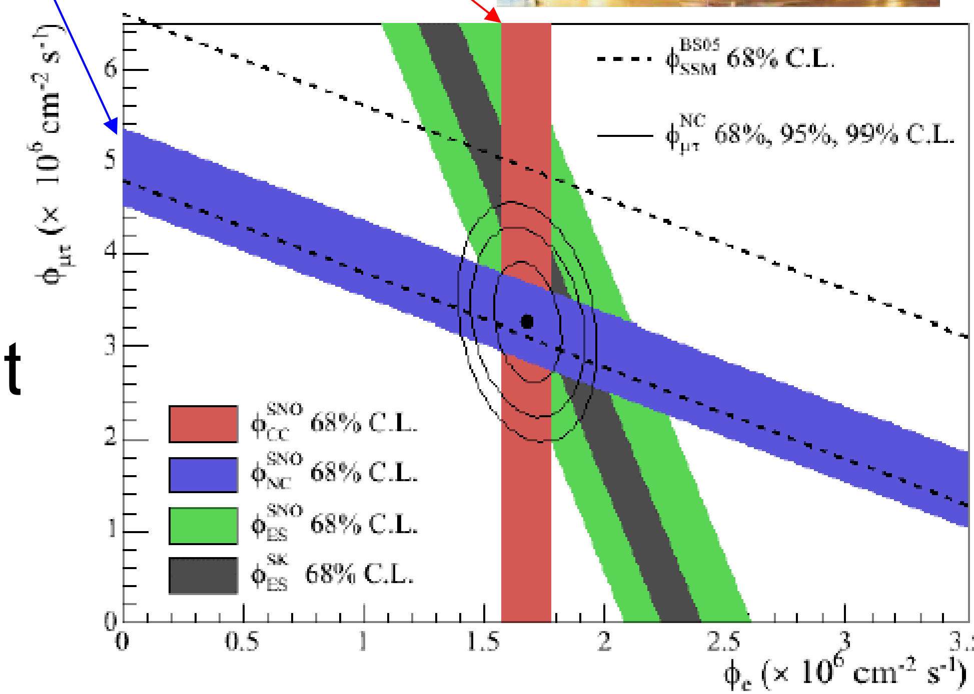
GALLEX
INTERNATIONAL SOLAR NEUTRINO RESEARCH COLLABORATION



Culmination: SNO

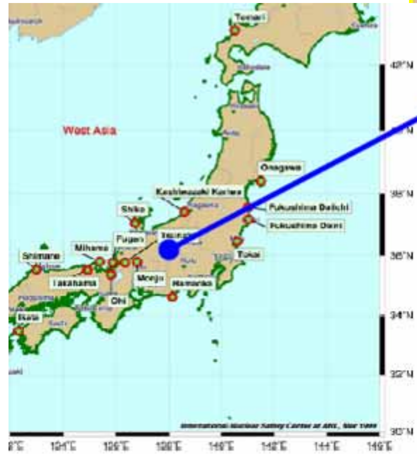


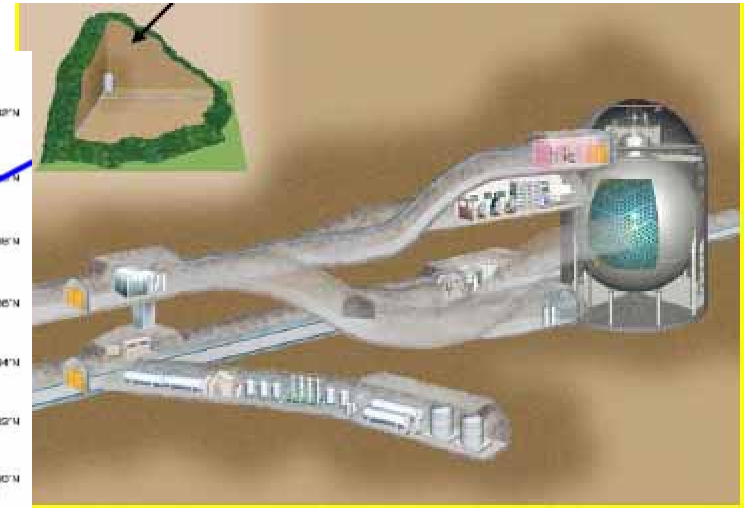
- D_2O target uniquely observes:
  - charged-current $\nu_e d \to ppe^-$
  - neutral-current $\nu_X d \to \nu_X pn$
- The former is only observed for ν_e (lepton mass)
- The latter for all types
- Solar flux is consistent with models
  - but not all ν_e at earth

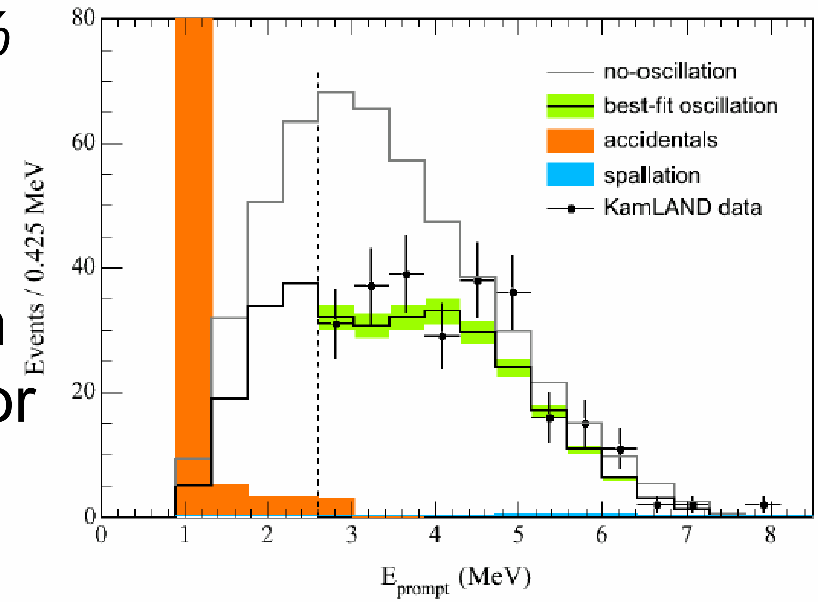


KAMLAND

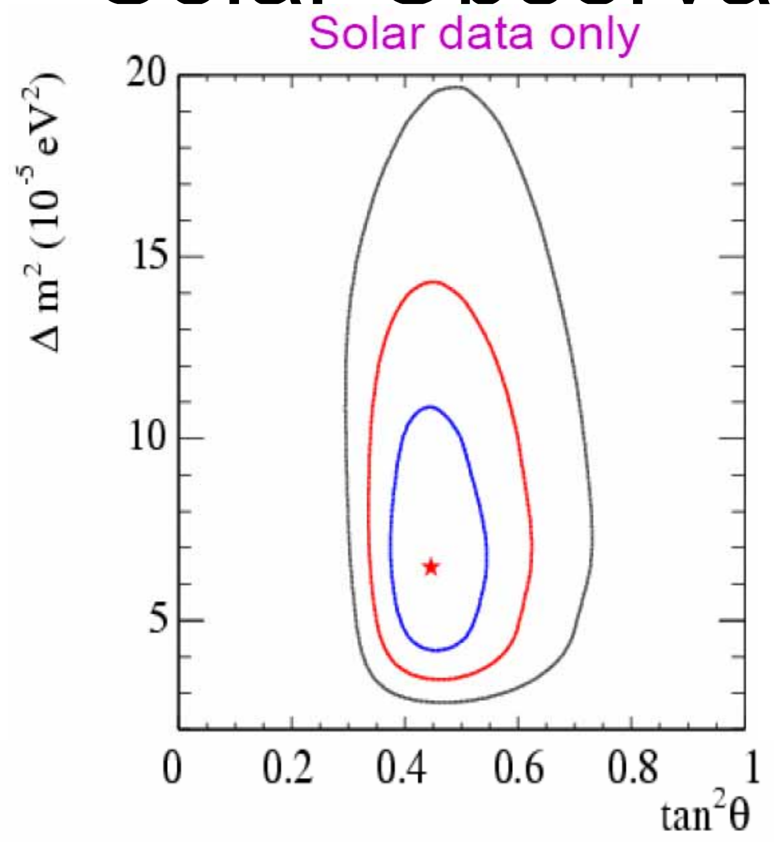
- Sources are Japanese reactors
  - *150-200 km* for most of flux. *Rate uncertainty ~6%*
- 1 kTon scint. detector in old Kamiokande cavern
  - overwhelming confirmation that neutrinos change flavor in the sun *via* matter effects



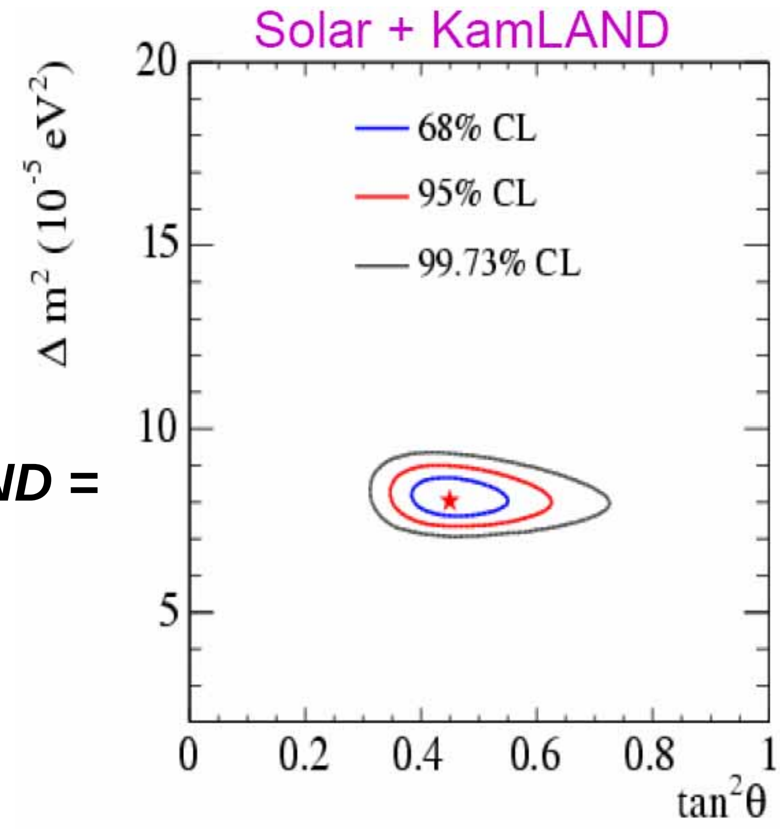




Solar Observations vs. KAMLAND

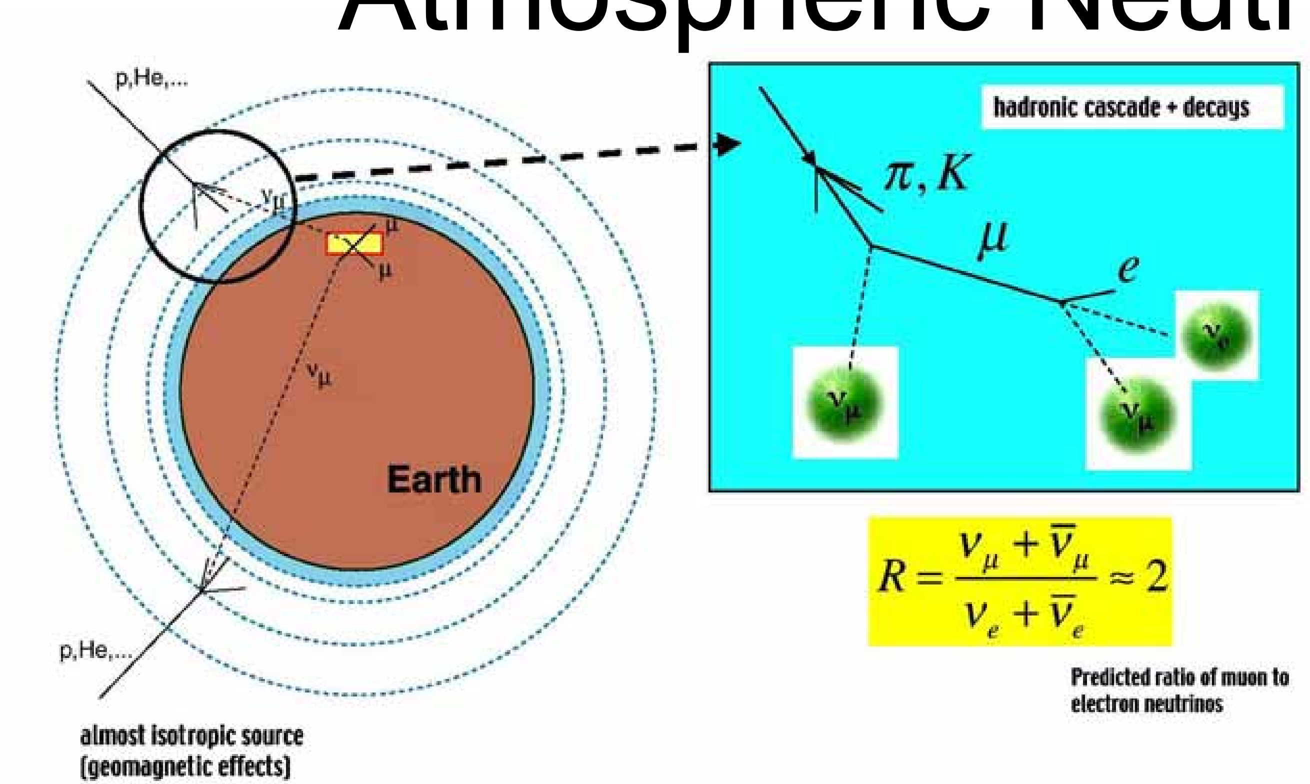


+ KAMLAND =



- Solar neutrino observations are best measurement of the mixing angle
- KAMLAND does better on δm^2_{12}

Atmospheric Neutrinos

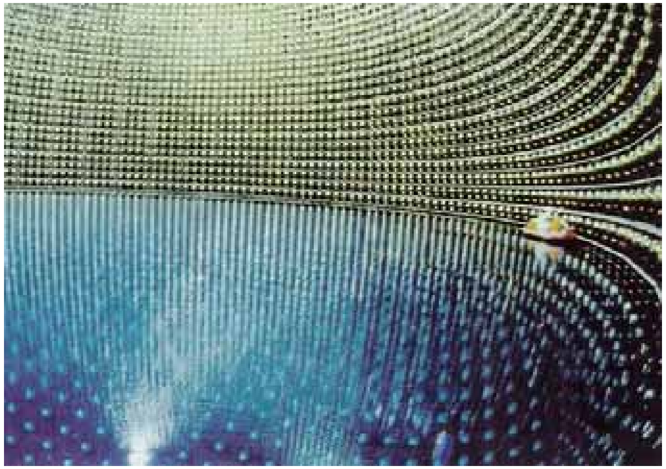


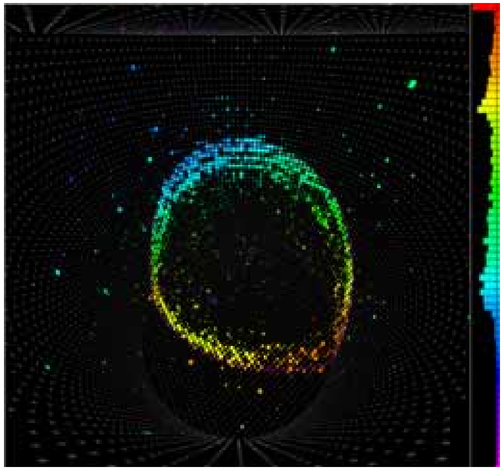
$$R = \frac{\nu_\mu + \overline{\nu}_\mu}{\nu_e + \overline{\nu}_e} \approx 2$$

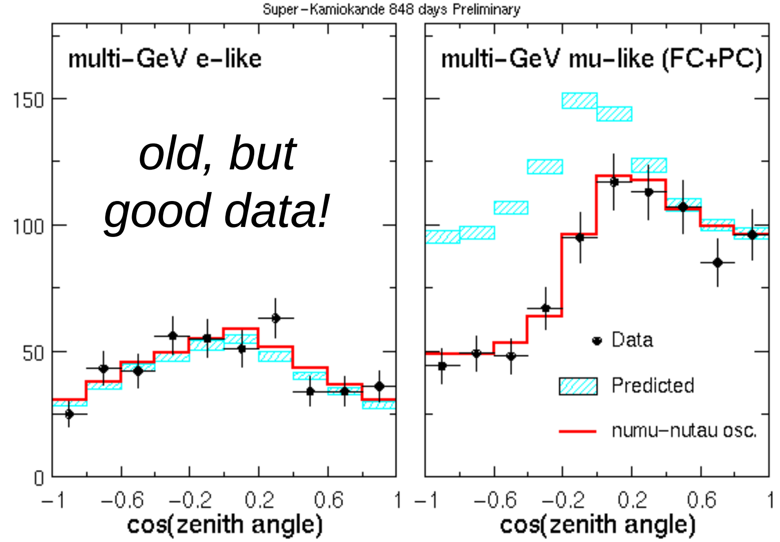
- Neutrino energy: few 100 MeV – few GeV
- Flavor ratio robustly predicted
- Distance in flight: ~20km (down) to 12700 km (up)

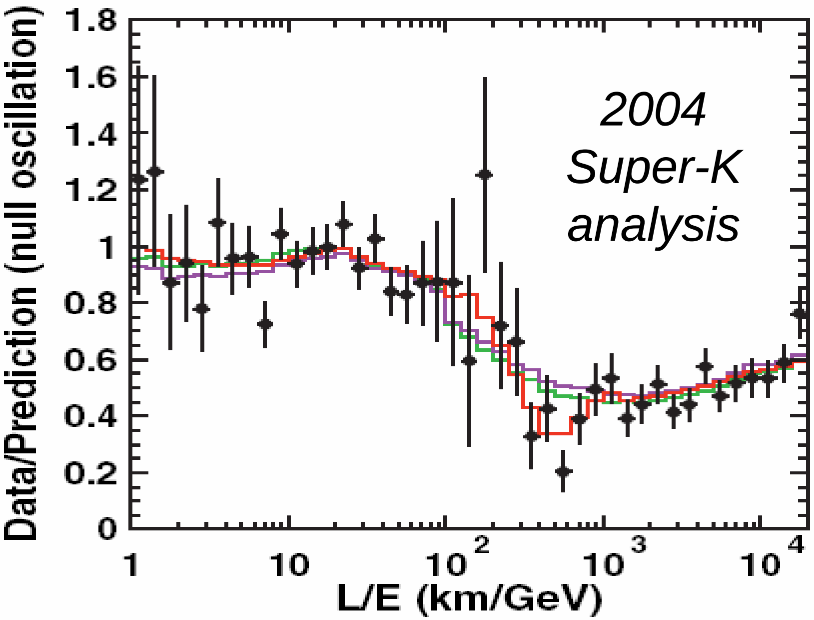
Super-Kamiokande

- Super-K detector has excellent e/μ separation







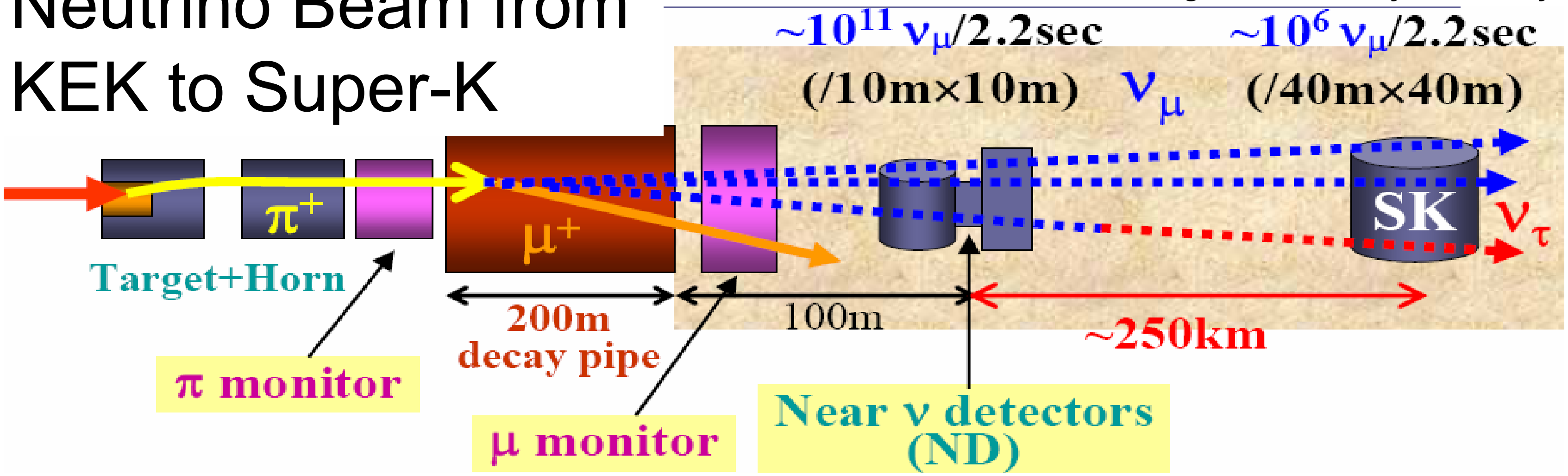


- Up / down difference!

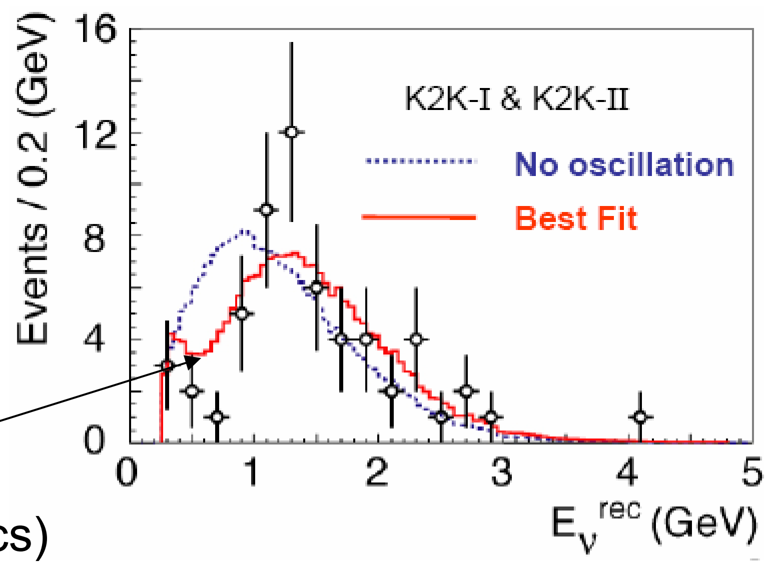
K2K

Neutrino Beam from KEK to Super-K

figures courtesy T. Nakaya

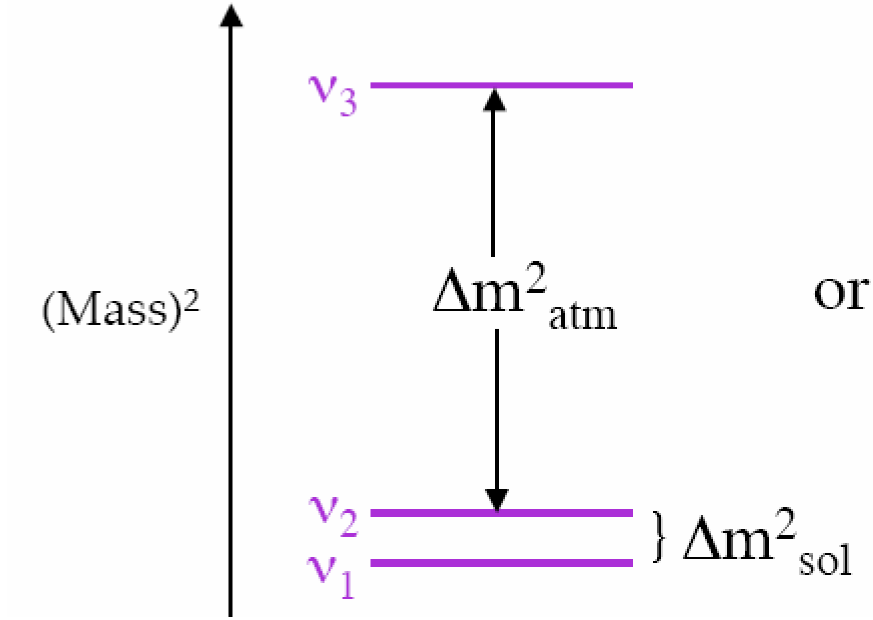


- Experiment has completed data-taking
  - confirms atmospheric neutrino oscillation parameters with controlled beam
  - constraint on δm^2_{23} (limited statistics)



Enough For Three Generations

figures courtesy B. Kayser



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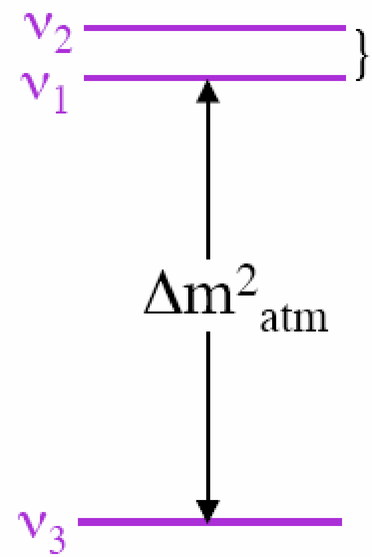


$\delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8\times10^{-5} eV^2$

$\delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5\times10^{-3} eV^2$

- Oscillations have told us the splittings in m^2, but nothing about the hierarchy
- *The electron neutrino potential (matter effects) can resolve this in oscillations, however.*

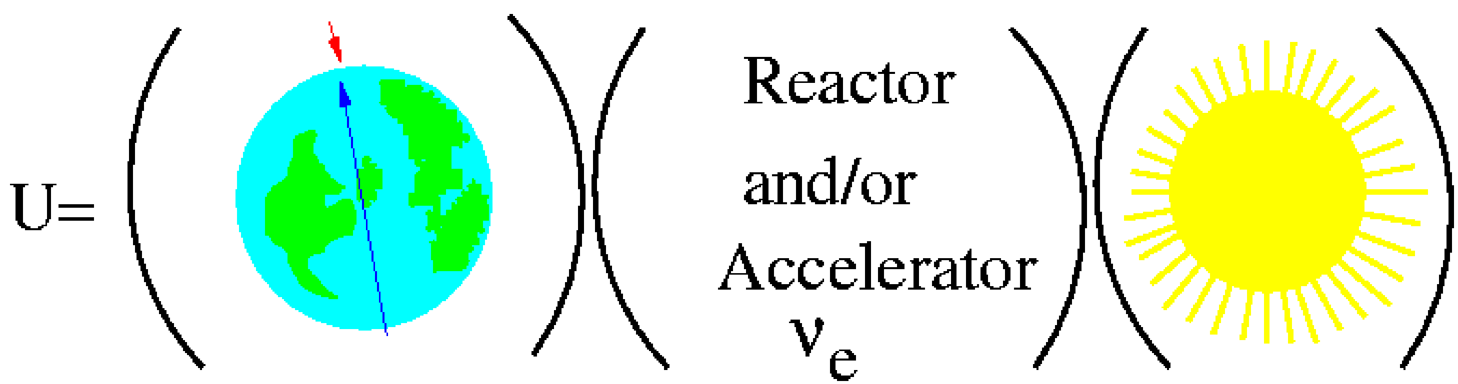
Three Generation Mixing

slide courtesy D. Harris

Lesson Learned from CKM: 3 mixing angles and a phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

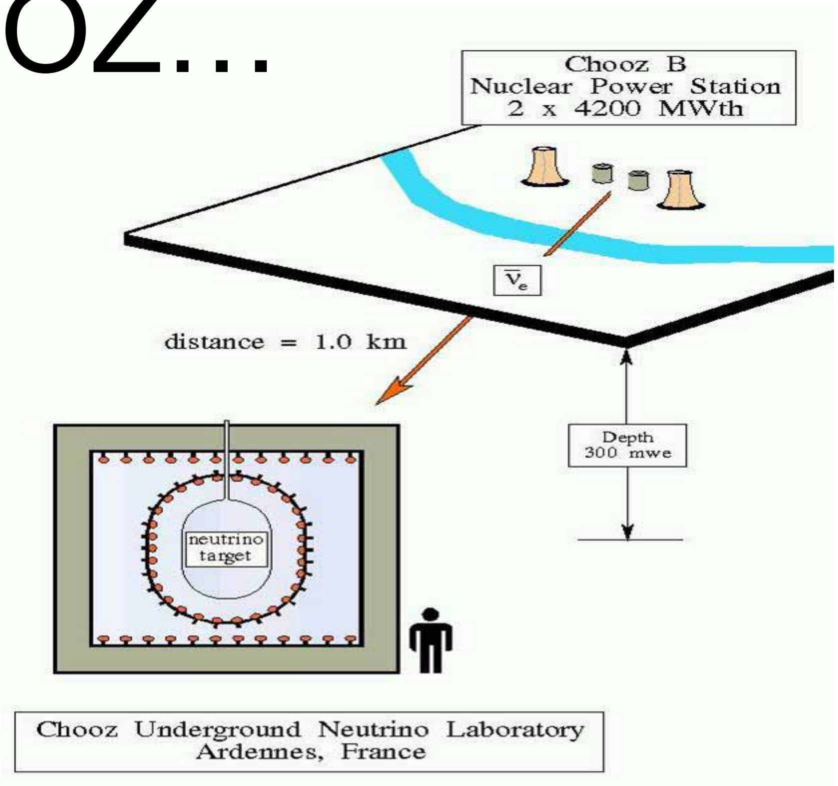
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

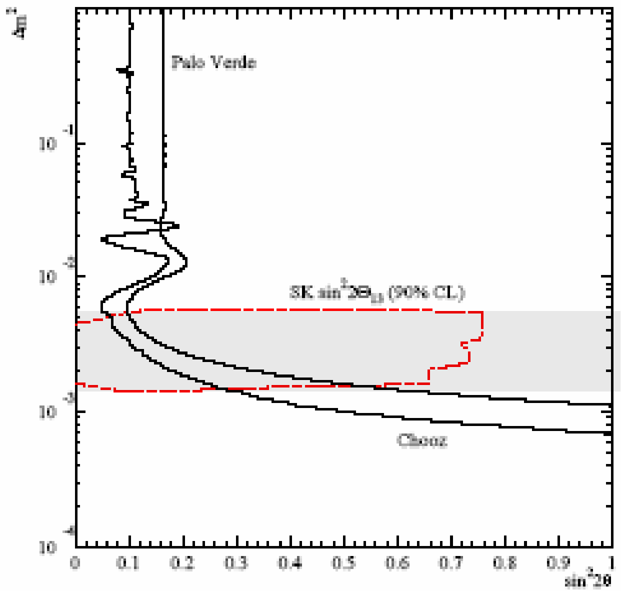


- Note the new mixing in middle, and the phase, δ

But CHOOZ…

- Like KAMLAND, CHOOZ and Palo Verde expt's looked at anti-ν_e from a reactor
  - compare expected to observed rate, σ~4%





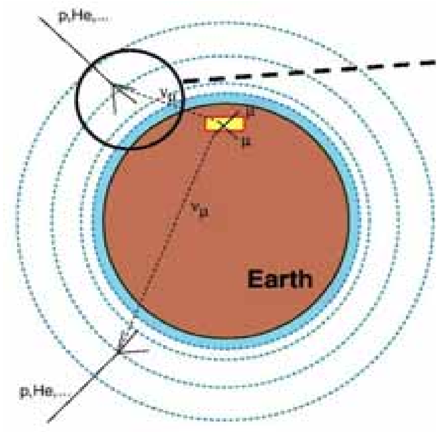
δm^2_{23}

- If electron neutrinos don't disappear, they don't transform to muon neutrinos
  - limits ν_μ->ν_e flavor transitions at and therefore $|U_{e3}|$ is "small"

Optimism has been Rewarded

"We live in the best of all possible worlds"

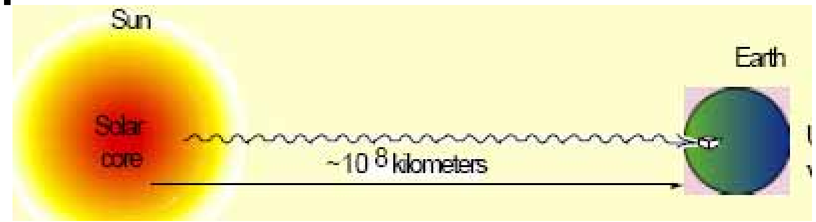
– Alvaro deRujula, Neutrino 2000



- By which he meant… had not

  $$E_{atm\,\nu}/R_{earth} < \delta m_{atm}^2 < E_{atm\,\nu}/h_{atm}$$

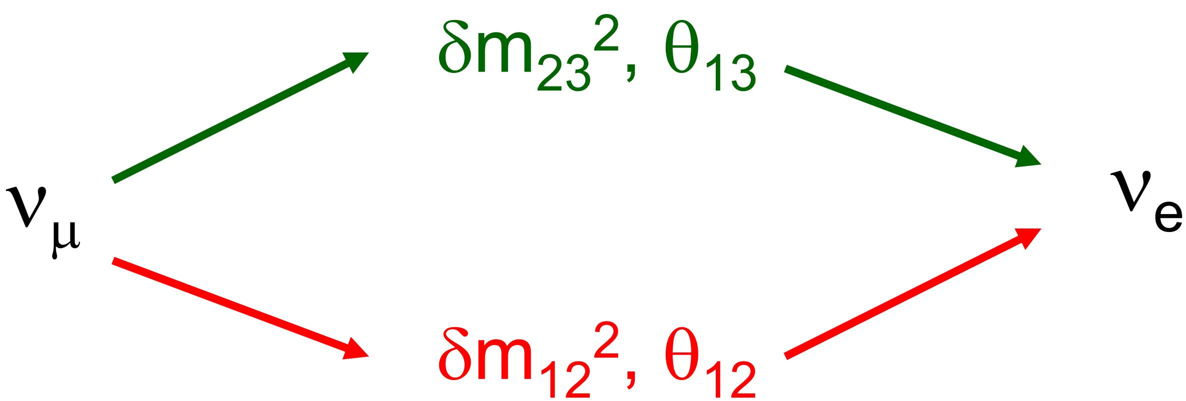
  and had not solar density profile and δm_{sol}^2 been well-matched…



- *We might not be discussing ν oscillations!*

Are Two Paths Open to Us?

- If "CHOOZ" mixing, θ_{13}, is small, but not too small, there is an interesting possibility



- At atmospheric L/E,

LARGE

SMALL

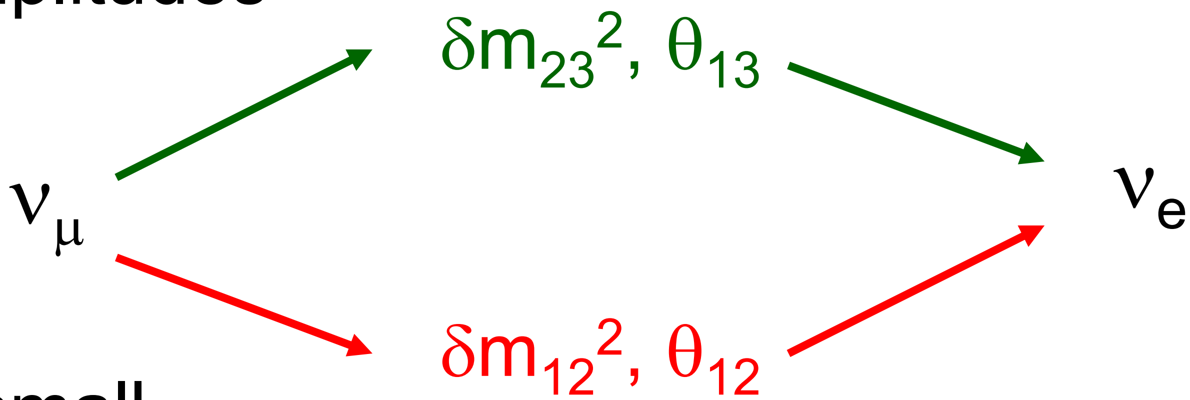
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

LARGE

SMALL

Implication of two paths

- Two amplitudes

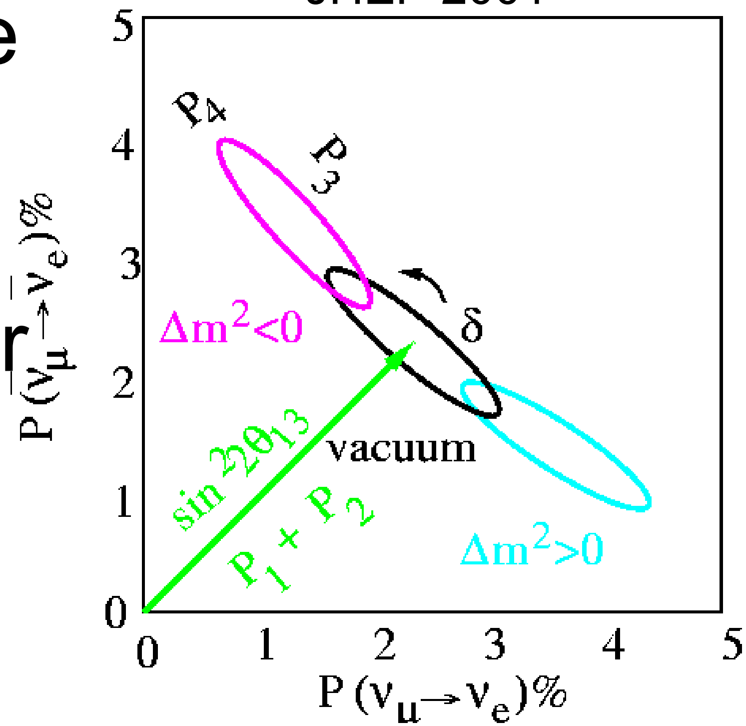


- If both small,
  but not too small,
  both can contribute ~ equally
- Relative phase, δ, between them can lead to CP violation (neutrinos and anti-neutrinos differ) in oscillations!

Leptons Have Rediscovered the Wonders of Three Generations!

- CP violation and matter effects lead to a complicated mix…
- CP violation gives ellipse but matter effects shift the ellipse in a long-baseline accelerator experiment…

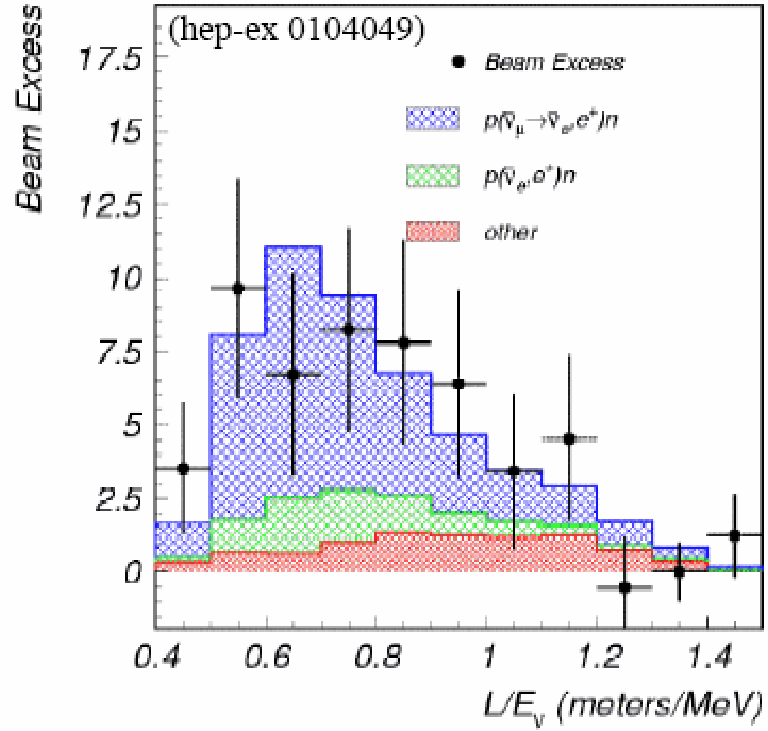
Minakata & Nunokawa JHEP 2001

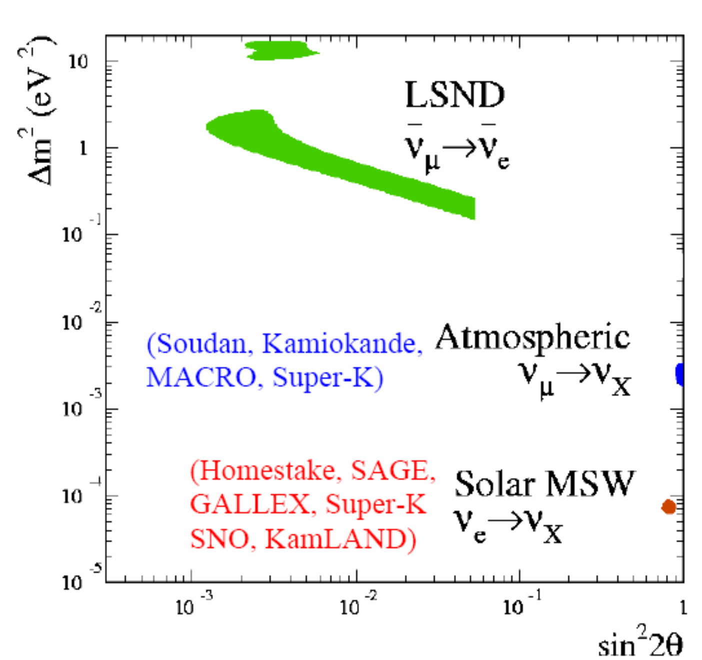


But LSND…

figures courtesy S. Brice

- LSND anti-ν_e excess
  - 87.9±22.4±6.0 events
  - statistically overwhelming; however…

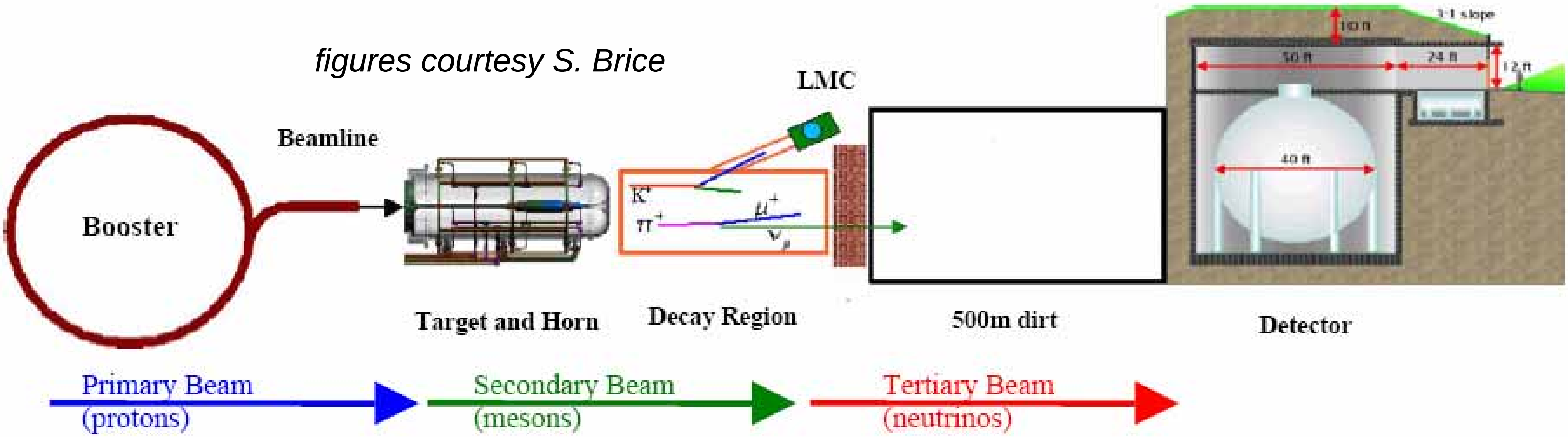




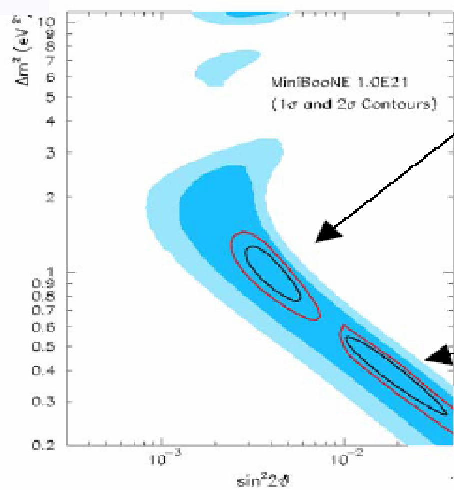
LSND	**$\delta m^2 \sim 0.1\text{-}1.0\ eV^2$**	**cannot be accommodated with only three neutrinos**
Atmos.	**$\delta m^2 \approx 2.5\times10^{-3}\ eV^2$**	
Solar	**$\delta m^2 \approx 8.0\times10^{-5}\ eV^2$**	

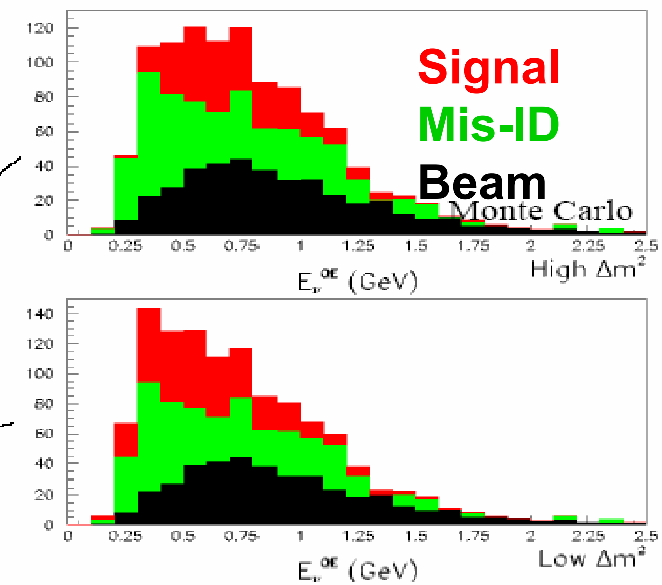
MiniBooNE

figures courtesy S. Brice



- A very challenging experiment!
- Have ~0.5E21 protons on tape
- First ν_e appearance results in late 2005





Next Steps
(Brazenly Assuming Three Neutrinos)

- MINOS and CNGS
- Reactors
- T2K and NOvA

graphical wit courtesy A. deRujula

- Mating Megatons and Superbeams
- Beta (ν_e) beams and neutrino factories ($\mu \rightarrow \nu_e$ and ν_μ)

Isn't all of this overkill?

- Disentangling the physics from the measurements is complicated (S. Parke)
- The short version of the story is that different measurements have different sensitivity to matter effects, CP violation
  - Matter effects amplified for long L, large E_ν
  - CP violation cannot be seen in disappearance (reactor) measurement $\nu_e \rightarrow \nu_e$

NuMI-Based Long Baseline Experiments

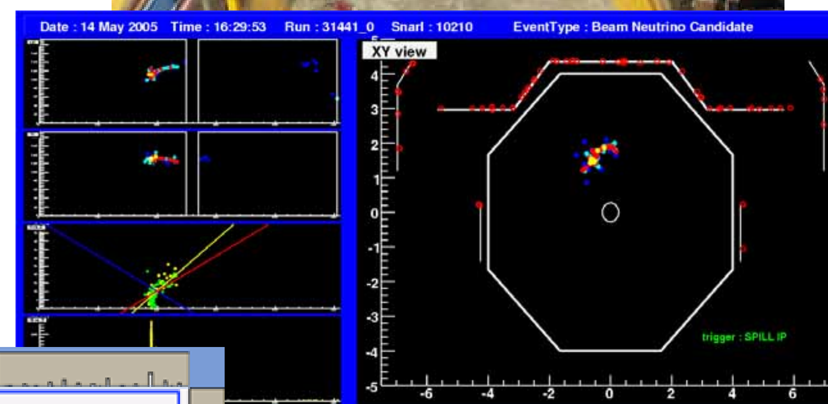
- 0.25 MWatt → 0.4 MWatt proton source
- Two generations:
  - MINOS (running)
  - NOvA (future) 15mrad Off Axis

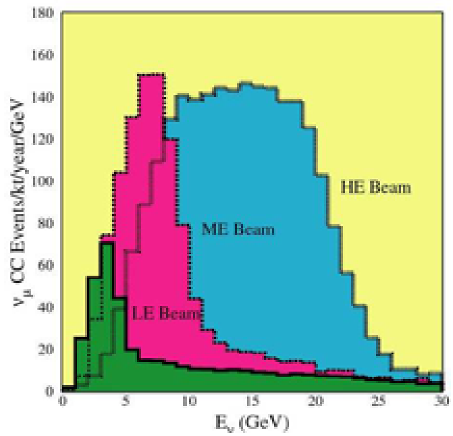
MINOS

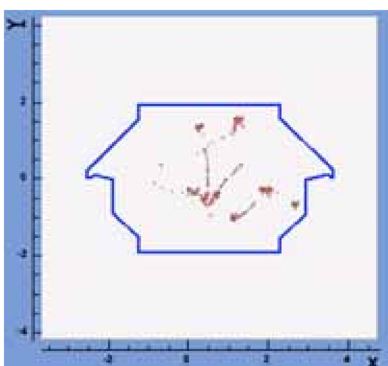
Goal: precise ν_μ disappearance measurement

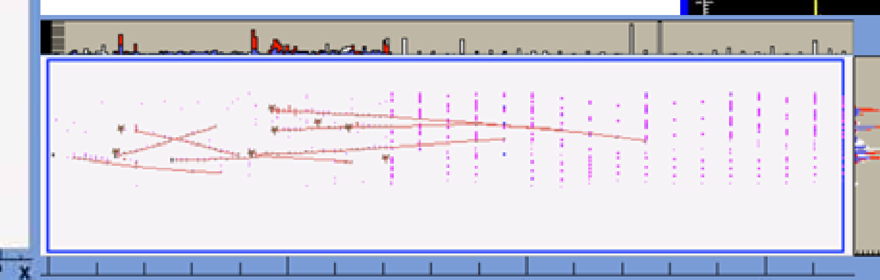
Gives $\boldsymbol{\delta m^2_{23}}$

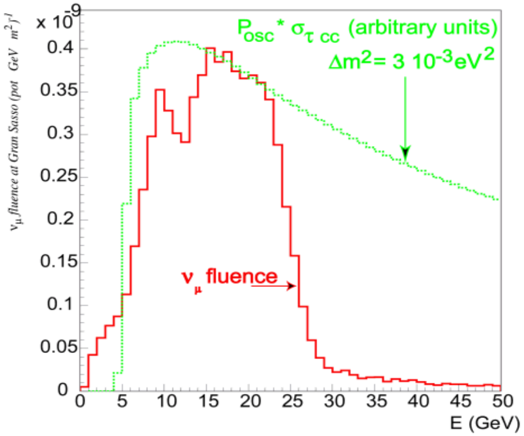
735km baseline
5.4kton Far Det.
1 kton Near Det.
Running since early 2005







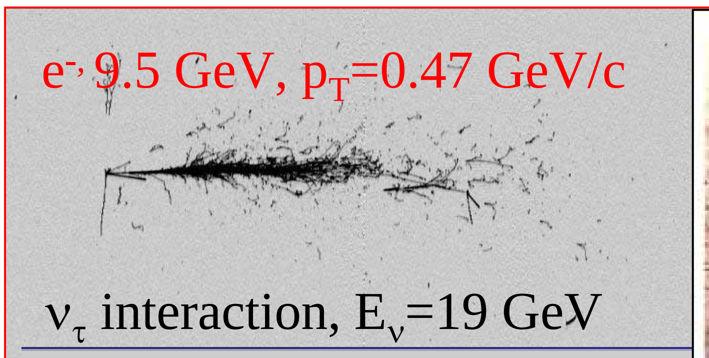


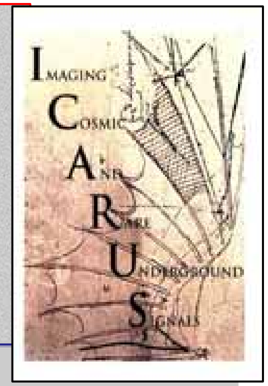


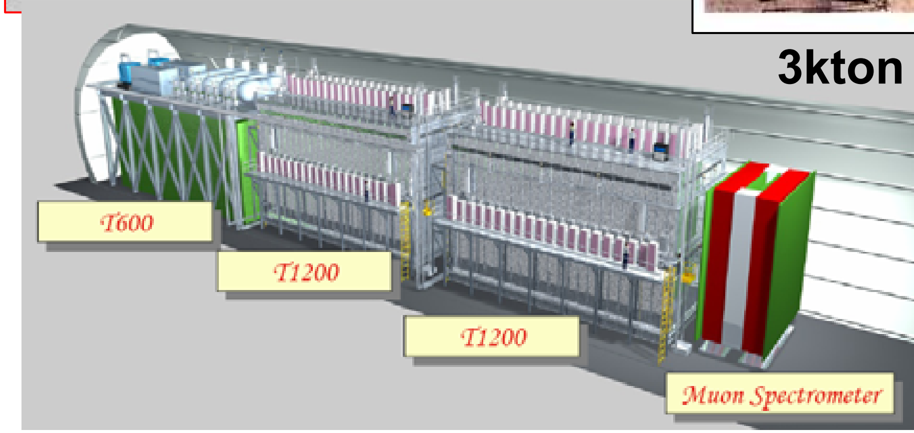
CNGS

Goal: ν_τ appearance

- 0.15 MWatt source
- high energy ν_μ beam
- 732 km baseline
- handfuls of events/yr

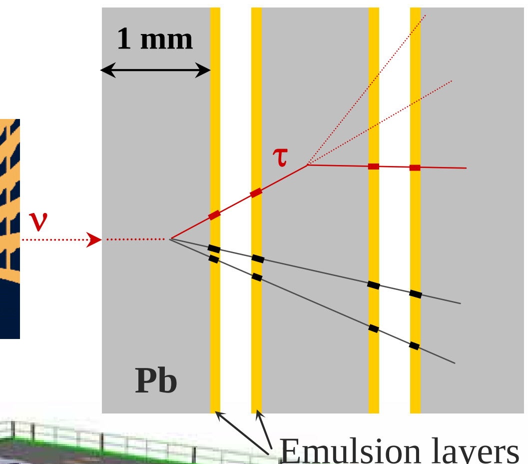


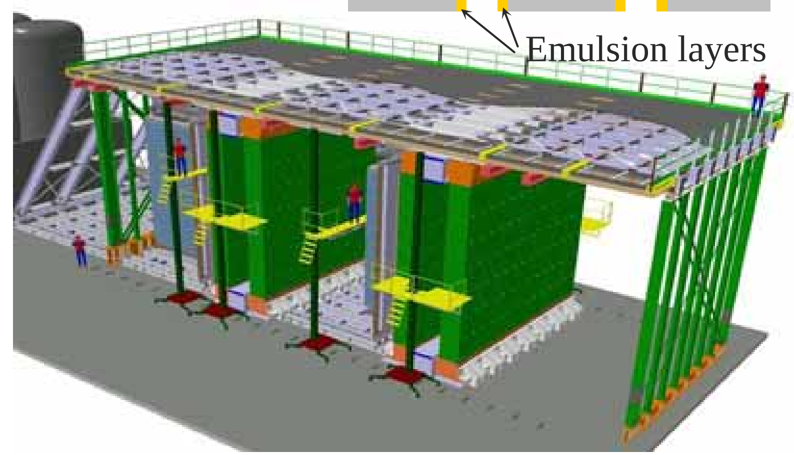




fiugres courtesy A. Bueno

1.8kTon

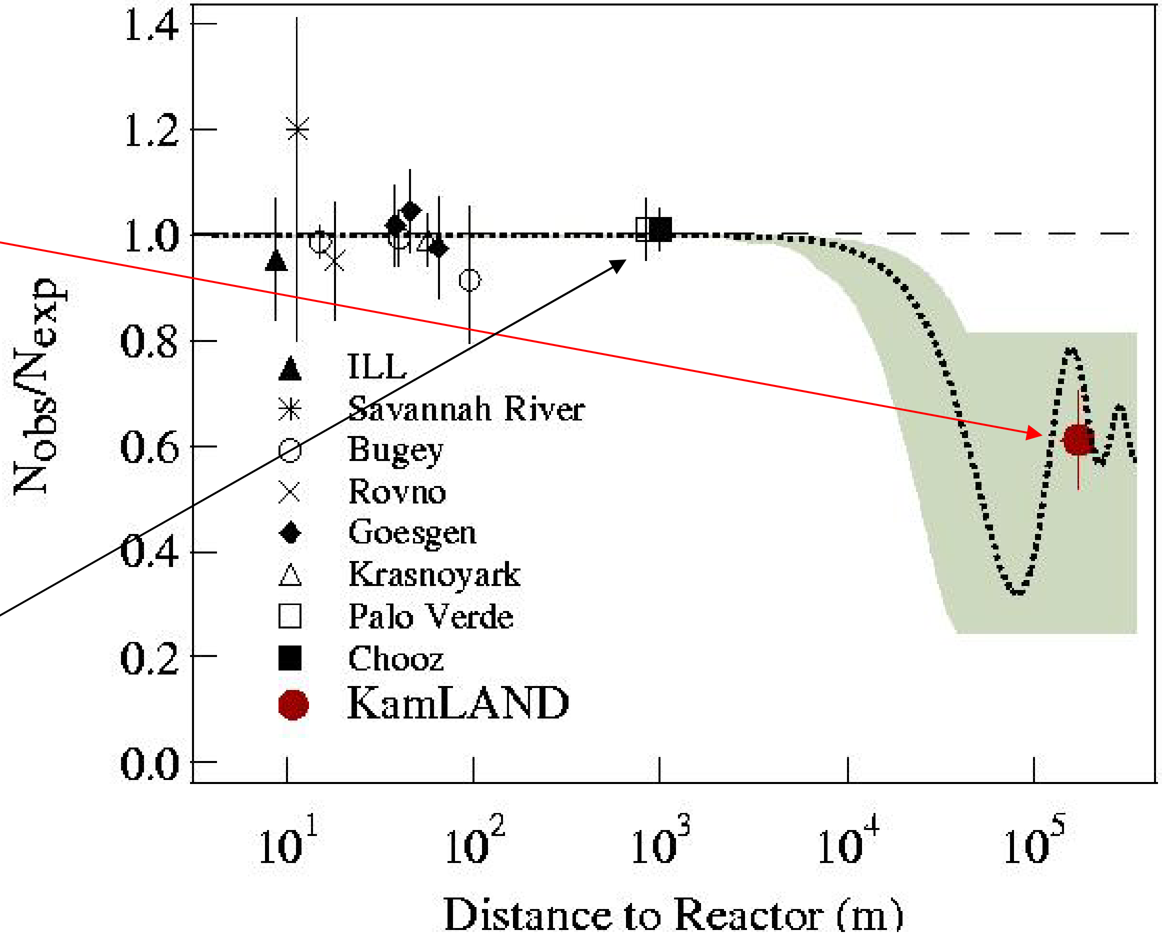




figures courtesy D. Autiero

Back to Reactors

- Recall that KAMLAND saw anti-ν_e disappearance at solar L/E
- Have not seen disappearance at atmospheric L/E



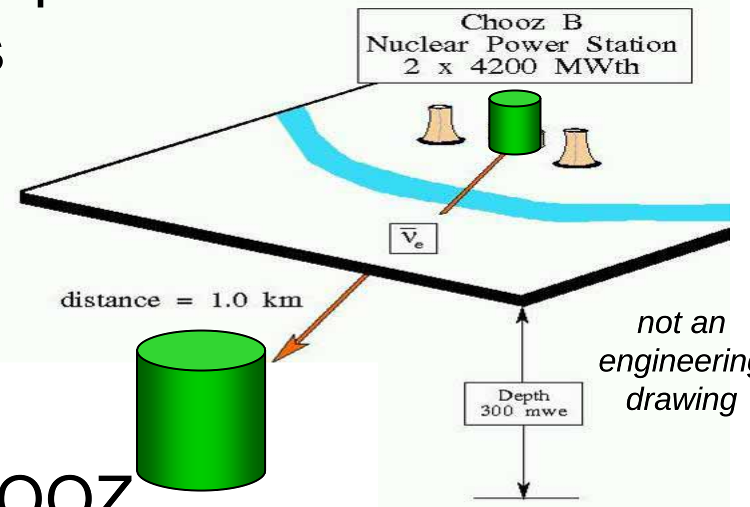
Why Reactors?

- CHOOZ (reactor) has left us without evidence of anti-ν_e disappearance indicating $|U_{e3}|>0$
  - *reactors are still the most sensitive probe!*
- CHOOZ used a single detector
  - therefore, dead-reckoning used to estimate neutrino flux from the reactor
  - could improve with a near/far technique
- KAMLAND has improved knowledge of how to reject backgrounds significantly

  (remember, their reactors are ~200 km away!)

How Reactors?

- To get from ~4% uncertainties to ~1% uncertainties, need a near detector to monitor neutrino flux
- For example, Double-CHOOZ proposes to add a second near detector and compare rates
  - new detectors with 10 ton mass
  - total error budget on rate ~2%
  - low statistics 10t limit spectral distortion, 1 km baseline likely shorter than optimum



not an engineering drawing

- Optimization beyond Double-CHOOZ…
  - ~100 ton detector mass
  - optimize baseline for δm^2_{23}
  - background reduction with active or passive shielding

Where Reactors?

Proposal	Baseline (Near/Far)	Overburden (Near/Far)	Detector Size (Near/Far)	Sensitivity ($\sin^2 2\theta_{13}$)
Double CHOOZ	0.2/1.05	50/300 mwe	10/10 t	0.03
Braidwood	0.2/1.7	450/450 mwe	130/130 t	0.01
Diablo Canyon	0.4/1.7	150/750 mwe	50/100 t	0.01
Angra, Brazil	0.3/1.5	200/1700 mwe	50/500 t	0.01
Daya Bay, China	0.3/1.8-2.2	300/1100 mwe	50/100 t	0.01

- A series of proposals with different technical choices
- All challenging experiments to limit systematics

Megawatt Class Beams

- J-PARC
  - initially 0.7 MWatts → 4 MWatts
- FNAL Main Injector
  - current goal 0.25 MWatts → 0.4 MWatts
  - future proton driver upgrades?
- Others?

J-PARC Facility

A Digression: Off-axis

- First Suggested by Brookhaven (BNL 889)
- Take advantage of Lorentz Boost and 2-body kinematics
- Concentrate ν_μ flux at one energy
- Backgrounds lower:
  - NC or other feed-down from high→low energy
  - ν_e (3-body decays)

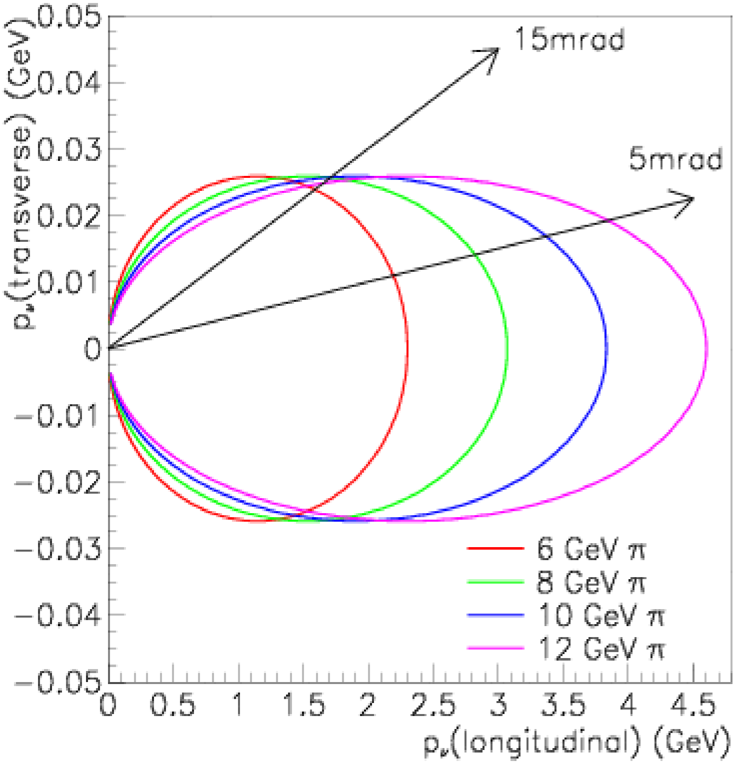
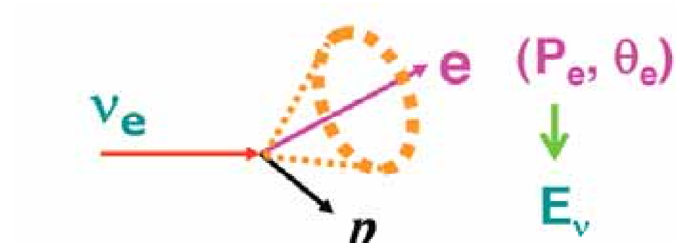
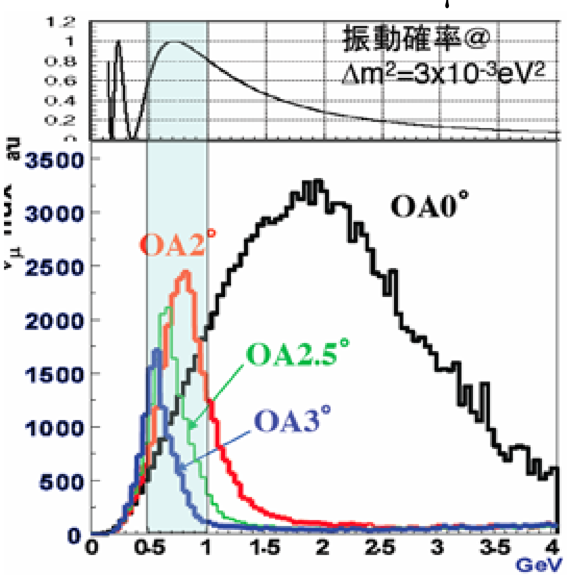


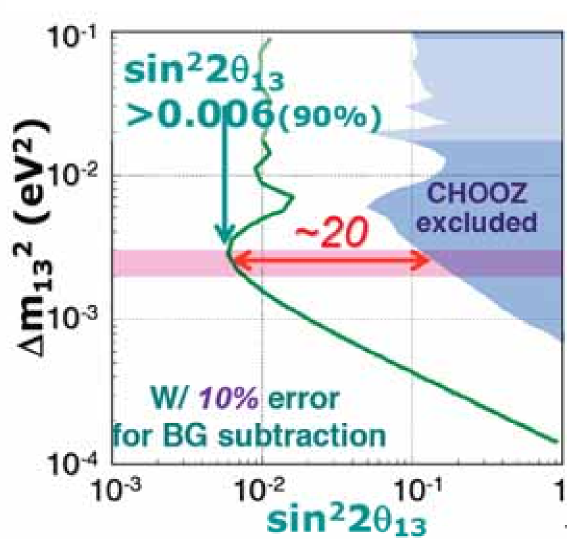
figure courtesy D. Harris

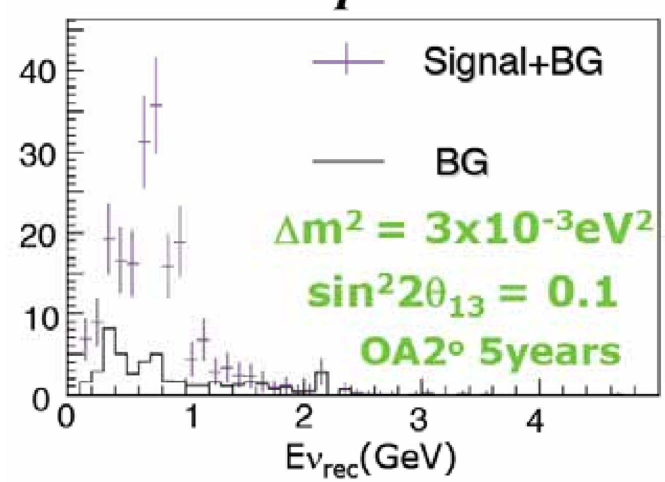
T2K

- Tunable off-axis beam from J-PARC to Super-K detector
  - beam and ν_μ backgrounds are kept below 1% for ν_e signal
  - ~2200 ν_μ events/yr (w/o osc.)









δ=0, no matter effects

figures courtesy T. Kobayashi

NuMI-Based Long Baseline Experiments

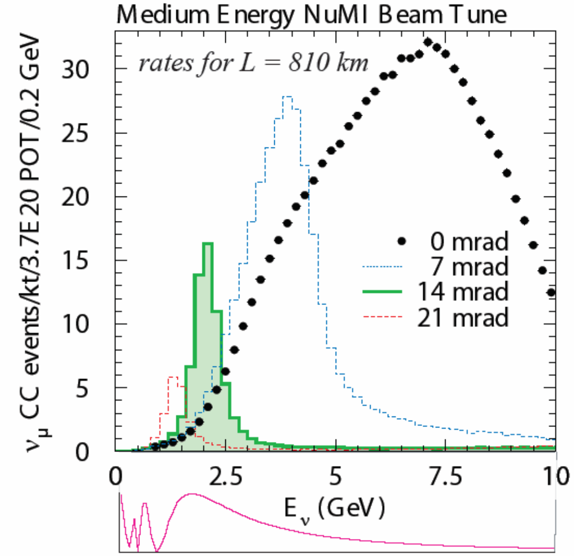
- 0.25 MWatt → 0.4 MWatt proton source
- Two generations:
  - MINOS (running)
  - NOvA (future) 15mrad Off Axis

NOνA

- Use Existing NuMI beamline
- Build new 30kTon Scintillator Detector
- 820km baseline--compromise between reach in θ_{13} and matter effects

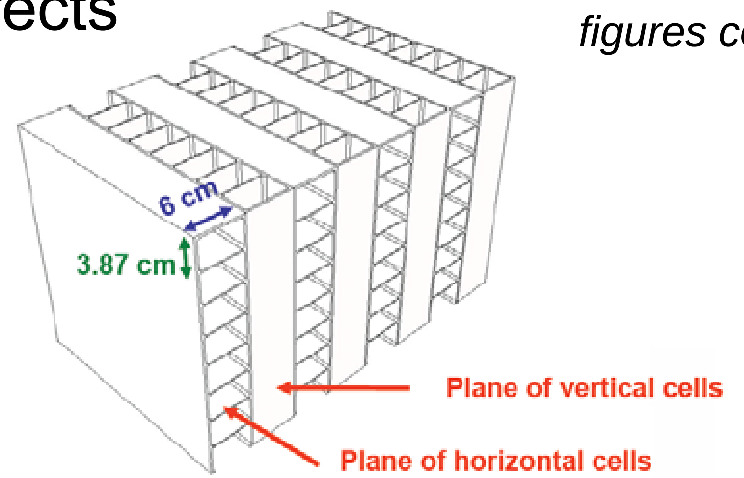
Goal:
ν_e appearance
In ν_μ beam

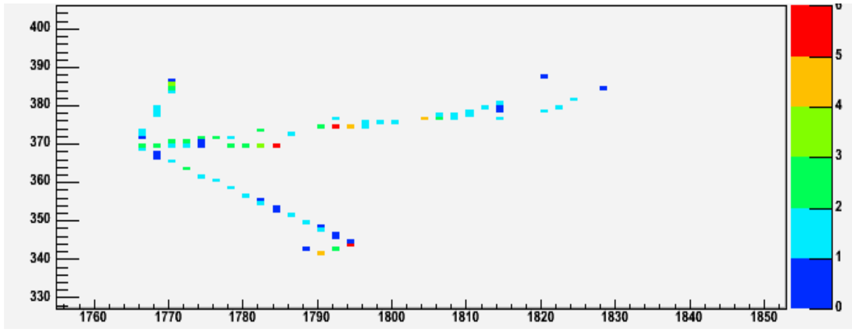
figure courtesy M. Messier



Assuming Δm^2=2.5x10^{-3}eV^2

figures courtesy J. Cooper





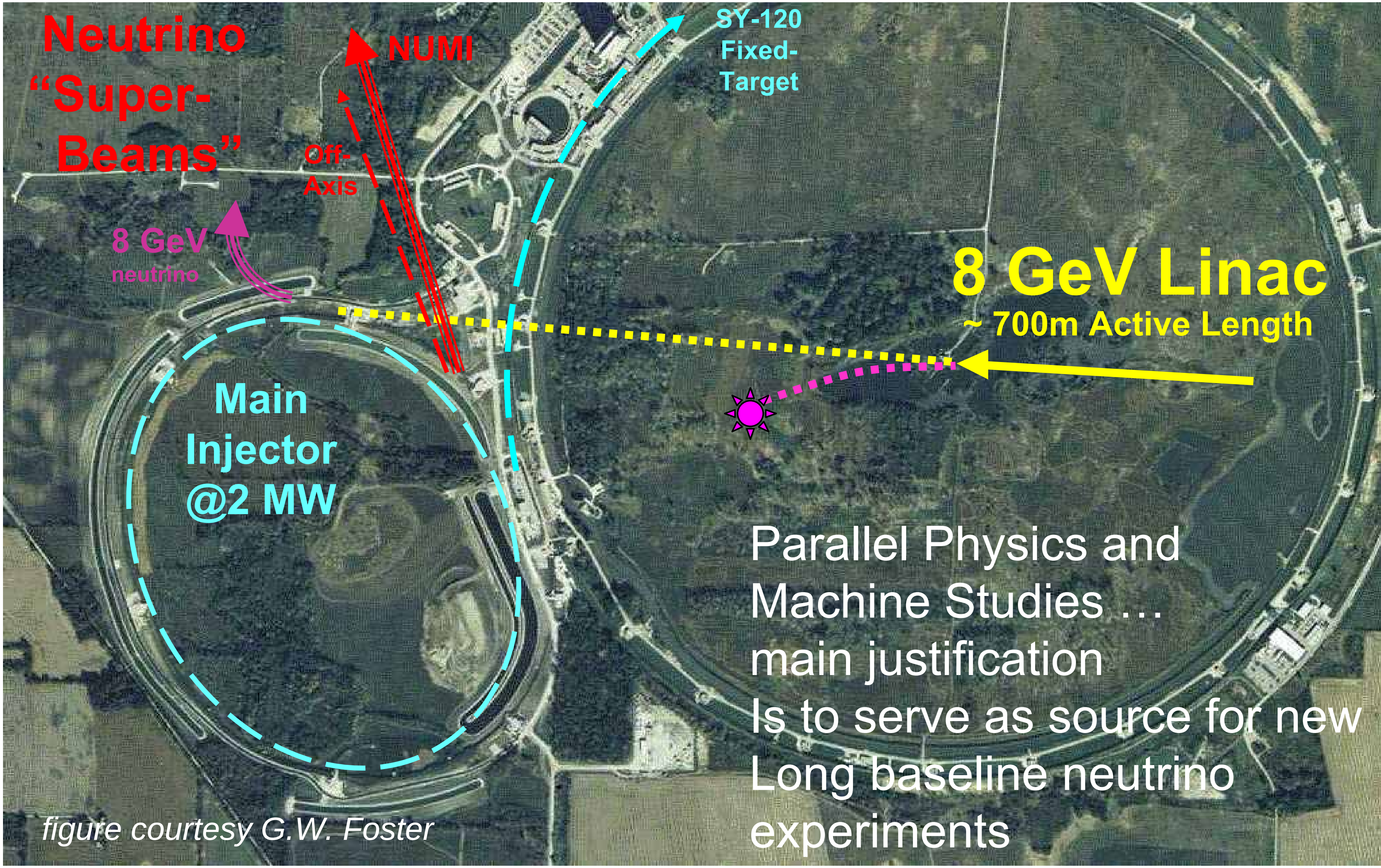
ν_e+A$\rightarrow$p π^+ π^- e$^-$

Future Steps after T2K, NOvA

- Beam upgrades (2x – 5x)
- Megaton detectors (10x – 20x)

- ***BUT***, it's hard to make such steps without encountering significant
  TECHNICAL DIFFICULTIES
  - hereafter "T.D."

TD: More Beam Power, Cap'n
Example: Fermilab Proton Driver



Parallel Physics and
Machine Studies …
main justification
Is to serve as source for new
Long baseline neutrino
experiments

TDs: Beamlines

pictures courtesy D. Harris

- Handling Many MWatts of proton power and turning it into neutrinos is not trivial!

NuMI tunnel boring machine. 3.5yr civil construction

NuMI downstream absorber. Note elaborate cooling. “Cost more than NuTeV beamline…” – R. Bernstein

NuMI Horn 2. Note conductors and alignment fixtures

NuMI Target shielding. More mass than far detector!

TDs: Detector Volume

- Scaling detector volume is not so trivial

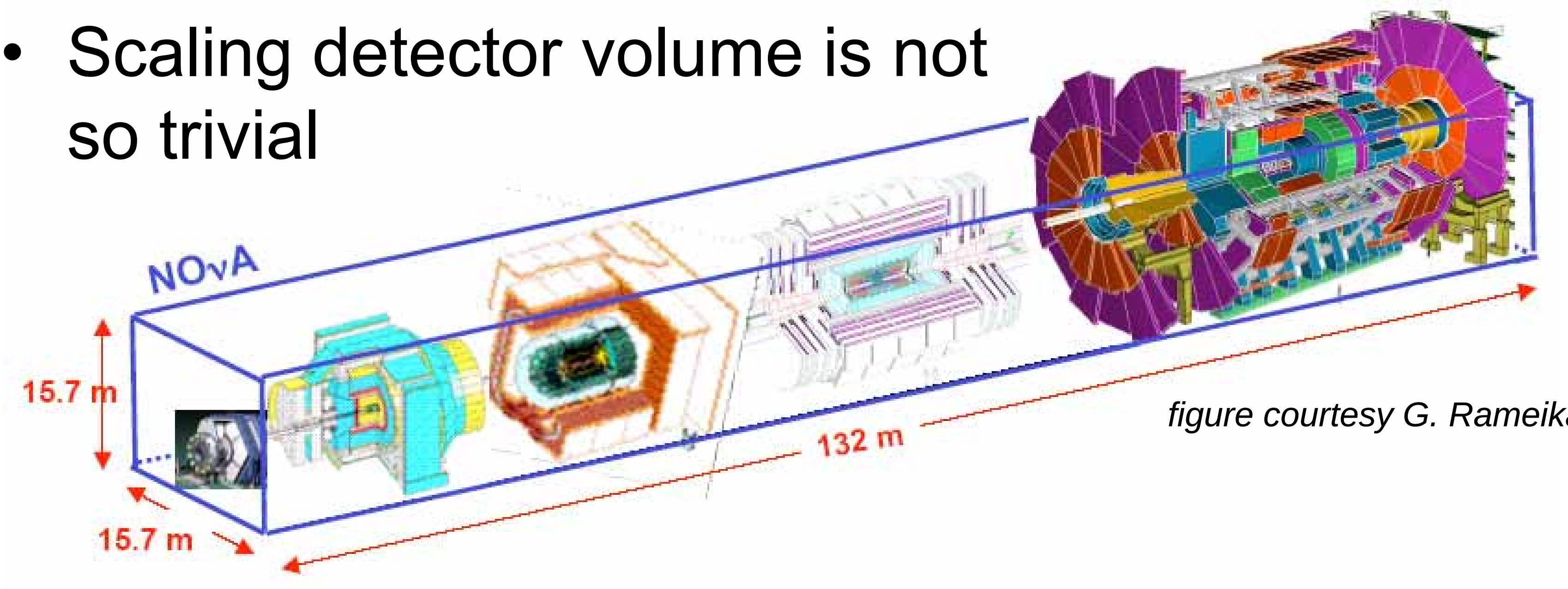
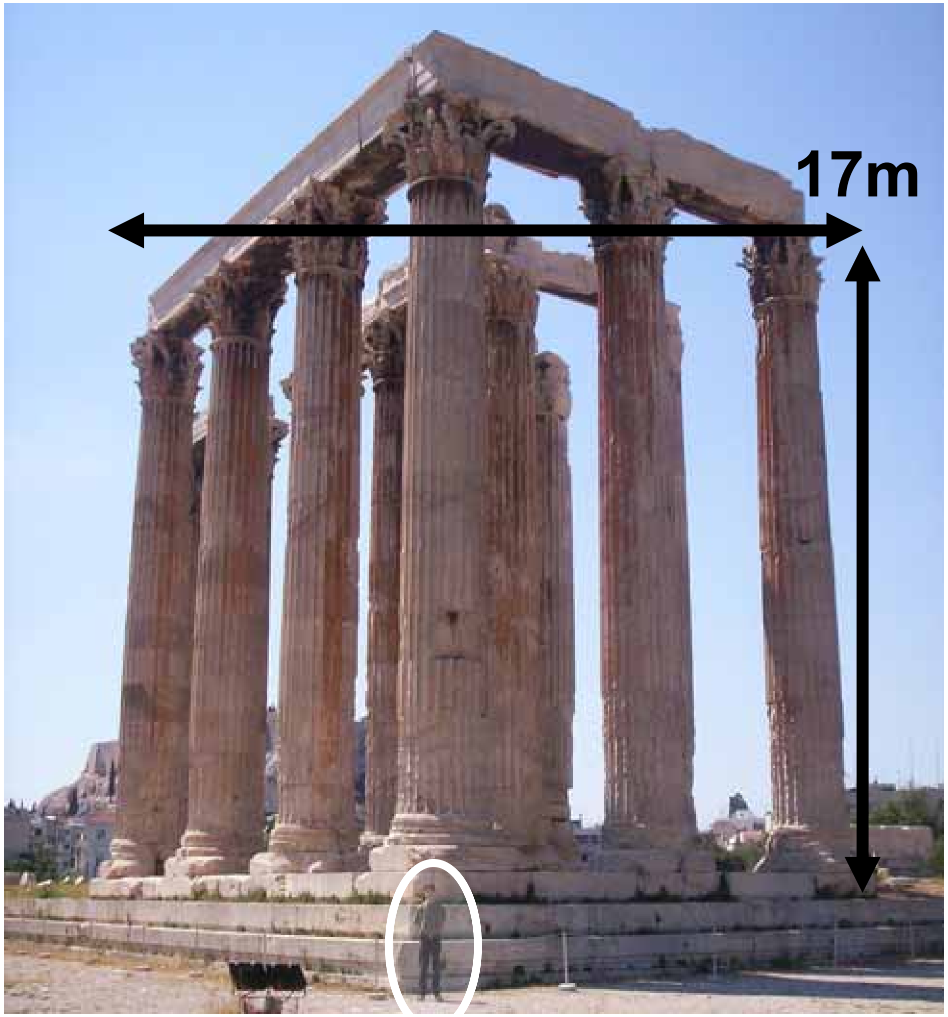


figure courtesy G. Rameika

- At 30kt NOvA is about the same mass as BaBar, CDF, Dzero, CMS and ATLAS combined…
  - want monolithic, manufacturabile structures
  - seek scaling as surface rather than volume if possible

For Perspective…

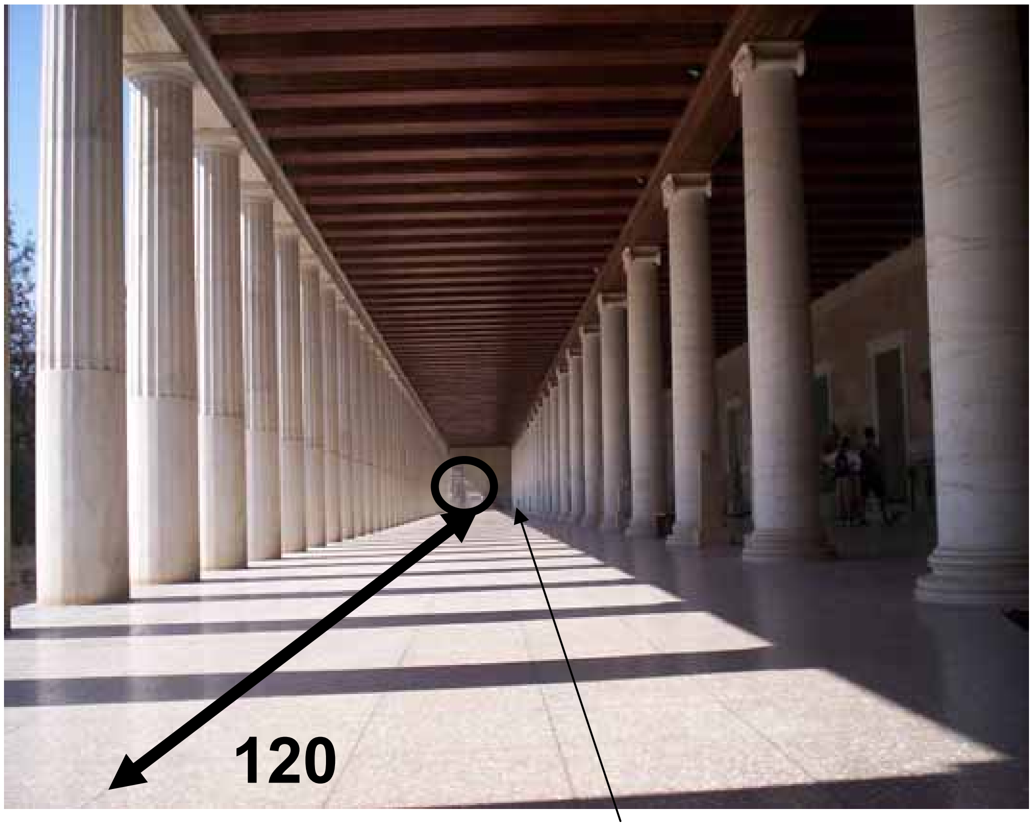


your speaker

- Consider the Temple of the Olympian Zeus…
- 17m tall, just like NOvA!
  - a bit over ½ the length
- It took 700 years to complete
  - delayed for lack of funding for a few hundred years
- Fortunately construction technology has improved
  - has the funding situation?

Perspective (cont'd)…

- Consider the Στοα τοψ Ατταλοψ …

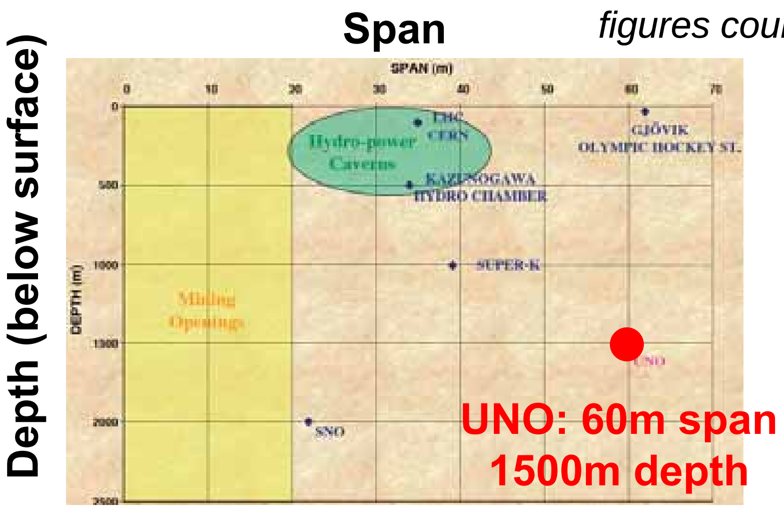


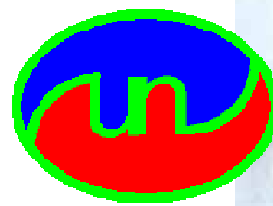
- 120m long, 10% less than NOvA
  - roughly the same height and width
- It was rebuilt over a mere four years
  - Funded by John D. Rockfeller
- Morals:
  - grand endeavors!
  - know who holds your checkbook…

TDs: Detector Volume (cont'd)

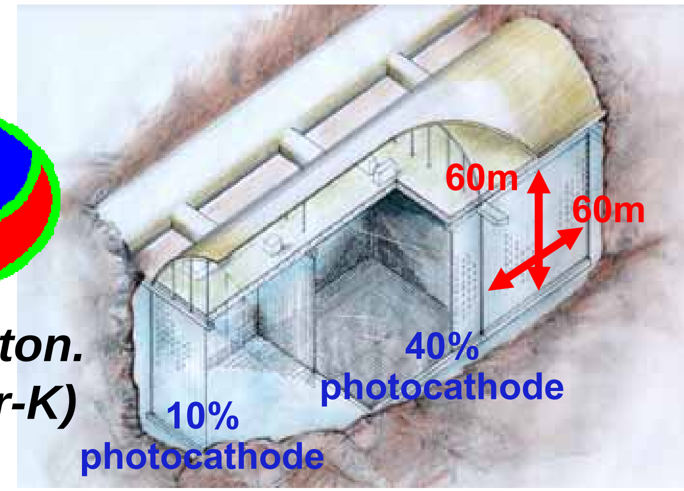
- For megatons, housing a detector is difficult!

figures courtesy C.-K. Jung

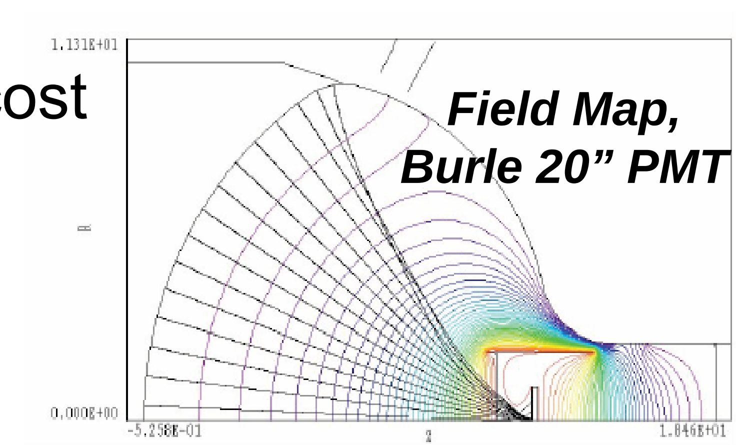




UNO. ~1Mton. (20x Super-K)



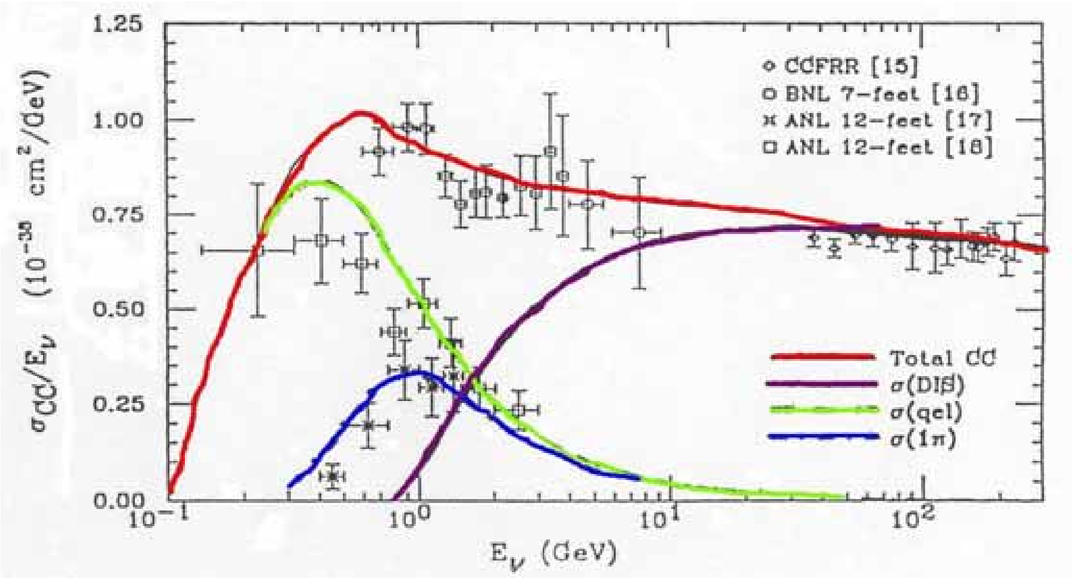
- Sensor R&D: focus on reducing cost
  - in case of UNO, large photocathode PMTs
  - goal: automated production, 1.5k$/unit

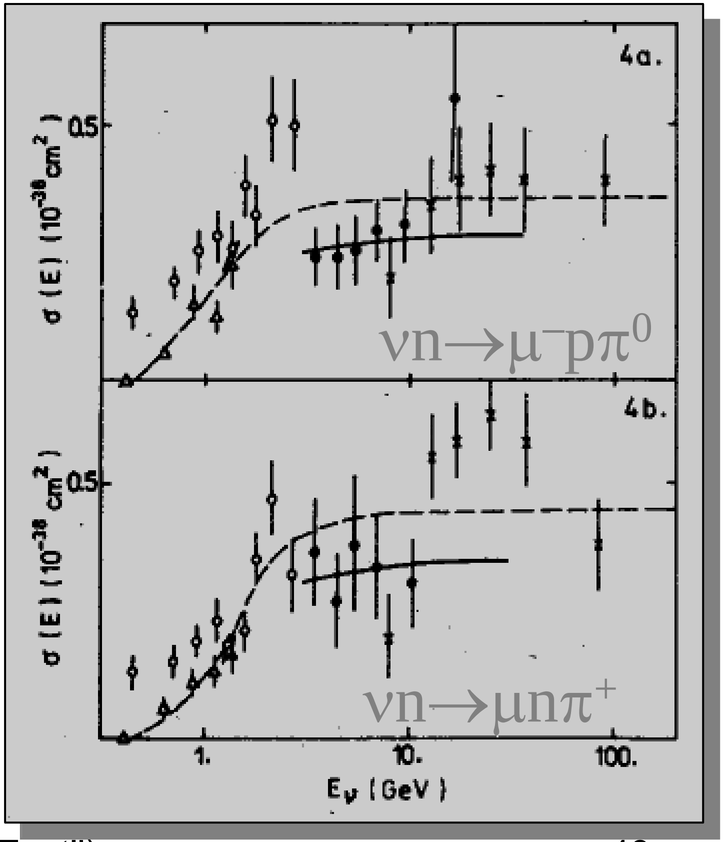


TDs: Neutrino Interactions

figures courtesy D. Casper, G. Zeller

- At 1-few GeV neutrino energy (of interest for osc. expt's)
  - Experimental errors on total cross-sections are large
    - almost no data on A-dependence
  - Understanding of backgrounds needs *differential* cross-sections on target
  - Theoretically, this region is a mess... transition from elastic to DIS

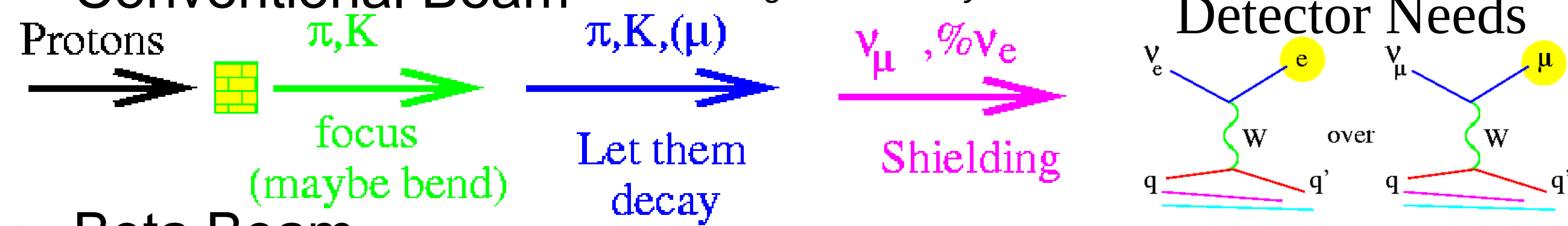




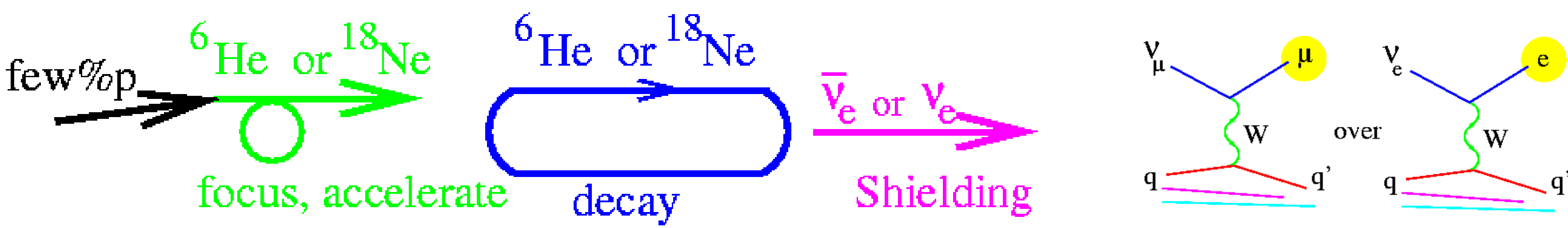
Futuristic Accelerator Beams

- Conventional Beam

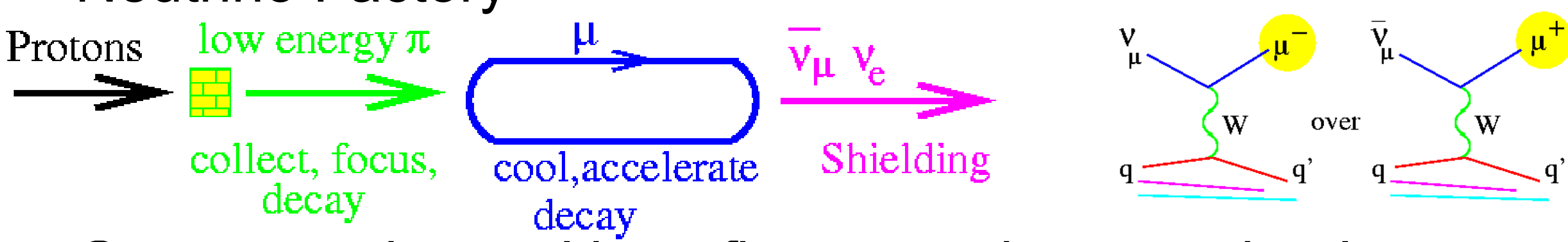
figures courtesy D. Harris



- Beta Beam



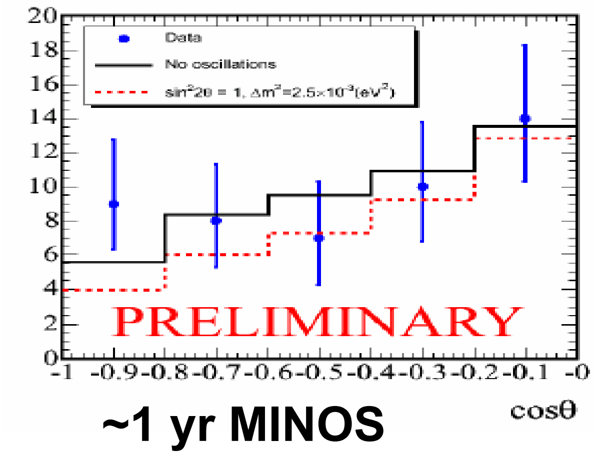
- Neutrino Factory



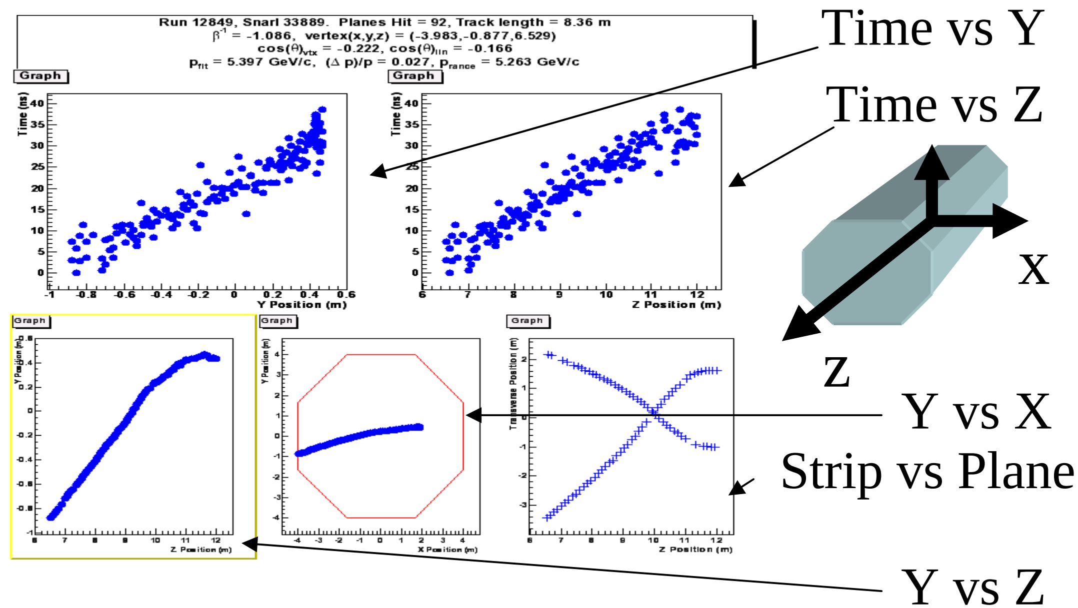
- Great experimental benefits to new beam technology, but beams are very challenging! And costly…

More to learn from the sky?

- Sign-separated atmospheric neutrinos
  - MINOS detector is first with this capability
  - determine charge from bend



~1 yr MINOS

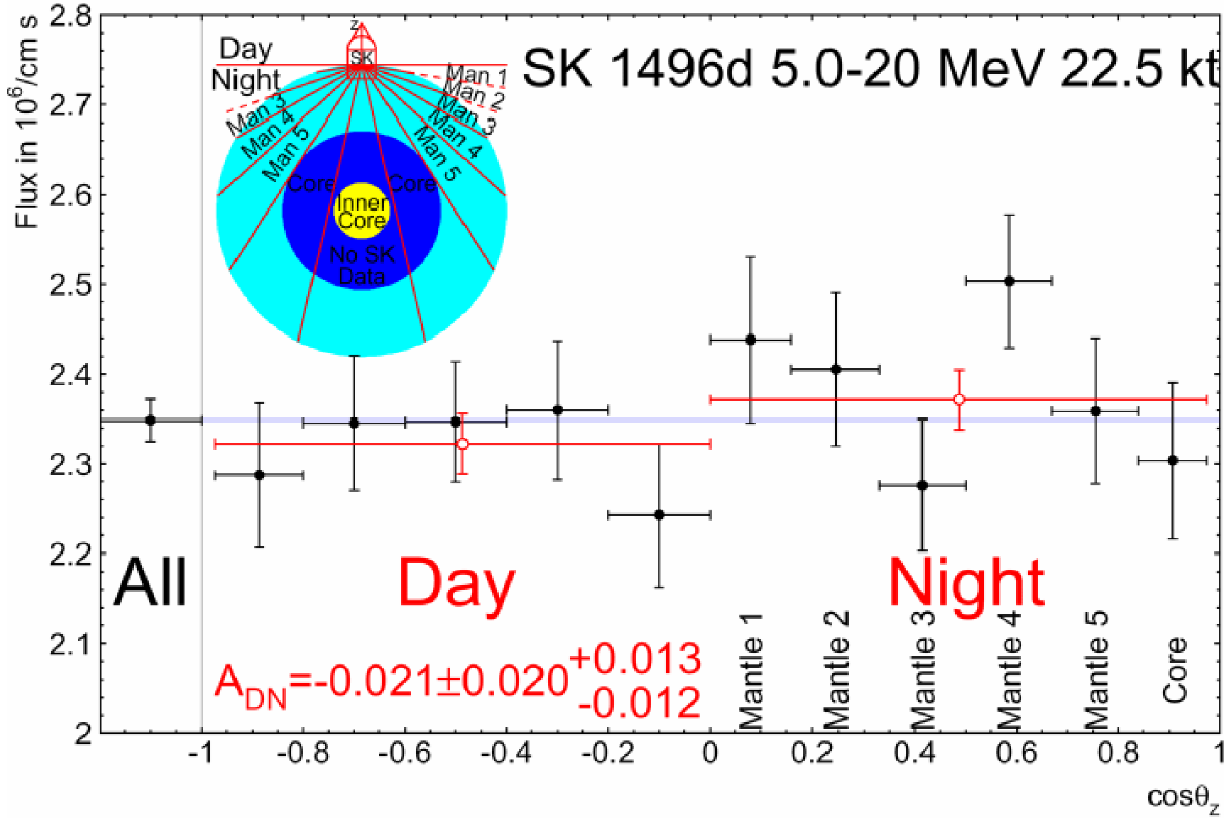


figures courtesy M. Bishai, H. Gallagher

- Why study neutrino vs. anti-neutrino oscillations?
  - possibility to test CPT violation scenarios if suggested by MiniBooNE and LSND results

Observing Matter Effected Oscillations

- We apparently have seen matter effects in the sun… can we verify it in the earth?
- Best results from Super-K
- Expect ~2% effect
  - Not there yet
- Interesting for future solar ν experiments…



The Broadest Goals

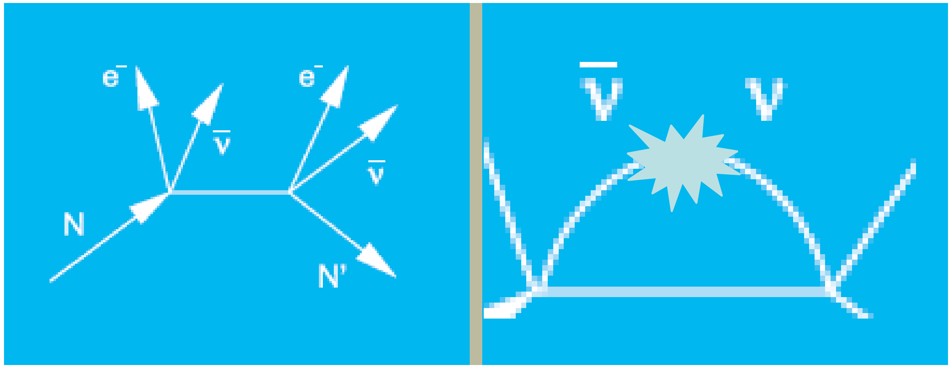
- Understand mixing of neutrinos
  - a non-mixing? CP violation?

- Understand neutrino mass
  - absolute scale and hierarchy
- Understand ν interactions
  - new physics? new properties?

- Use neutrinos as probes
  - nucleon, earth, etc.

Neutrinoless Double-Beta Decay

- Double beta decay
  $$^{A}\mathrm{Z} \rightarrow {}^{A}(\mathrm{Z+2}) + 2\beta^{-} + 2\overline{\nu}_e$$
  is a rare, but observed process



graphics courtesy Symmetry magazine

- "Neutrinoless" implies that the neutrino is its own anti-particle (Majorana particle)

$$\Gamma^{0\nu\beta\beta} = m_{\beta\beta}{}^{2} \times (\text{phase space}) \times (\text{nucl. matrix elems.})$$

calculable

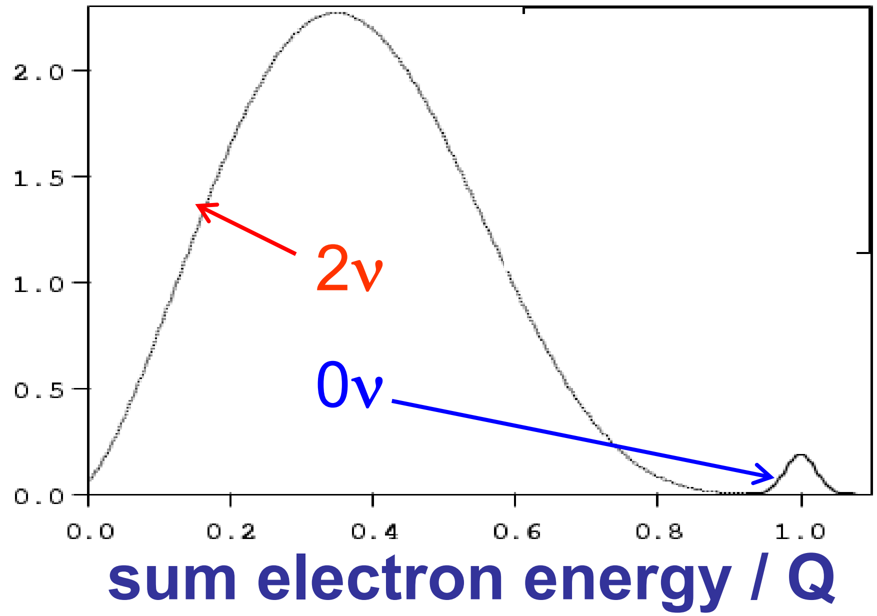
evaluable w/ largish uncertainties

- The prize: $m_{\beta\beta} = \left| \sum_i |U_{ei}|^2 m_i e^{i\alpha_i} \right|$

(α_i is a "Majorana phase". Please look it up because I'm not going there…)

Experimental Challenges

- Observables: electron energy, and the final state nucleus (EXO)
  - Electron energy requires excellent resolution and low non ββ backgrounds
  - Tagging the final state nucleus is “finding a needle in a haystack”



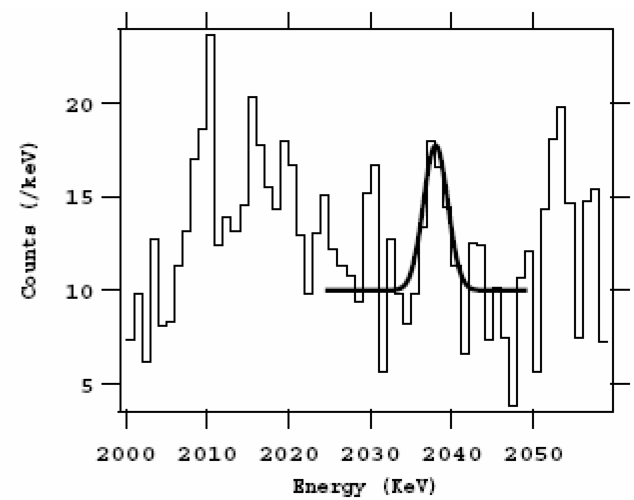
- Must also have significant quantities of ββ decaying isotopes
  - not necessarily easy to purify. good detector material?

Current Results to Date

- Results
- To notice:
  - ^{76}Ge, ^{130}Te have large quantities, best limits so far
  - There is a claimed observation
    - controversial
    - significant non-$\beta\beta$ backgrounds (hard-to-predict Bi lines)

Isotope	Exposure (kmole-y)	Background (counts)	Half-Life Limit (y)	$\langle m_{\beta\beta} \rangle$ (meV)
^{48}Ca	5×10^{-5}	0	$> 1.4 \times$	
^{76}Ge	0.467	21	$\times$	< 350[106]
^{76}Ge	0.117	3.5	$\times$	$< 330 - 1350$[107]
			$\times$	
^{76}Ge	0.943	61	$\times$	$= 440$[103]
^{100}Mo	5×10^{-4}	4	$> 5.5 \times 10^{22}$	< 2100[109]
^{116}Cd	1×10^{-3}	14	$> 1.7 \times 10^{23}$	< 1700[110]
			$> 7.7 \times 10^{24}$	$< 1100 - 1500$[111]
^{130}Te	0.025		$> 5.5 \times 10^{23}$	$< 370 - 1900$[112]
^{136}Xe	7×10^{-3}	16	$> 4.4 \times 10^{23}$	
^{150}Nd	6×10^{-5}	0	$> 1.2 \times 10^{21}$	< 3000[114]

figure and table from APS ν report: direct mass group



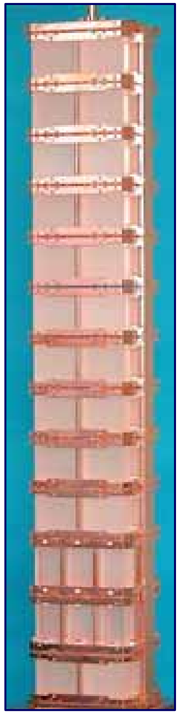
$0\nu\beta\beta$ Future

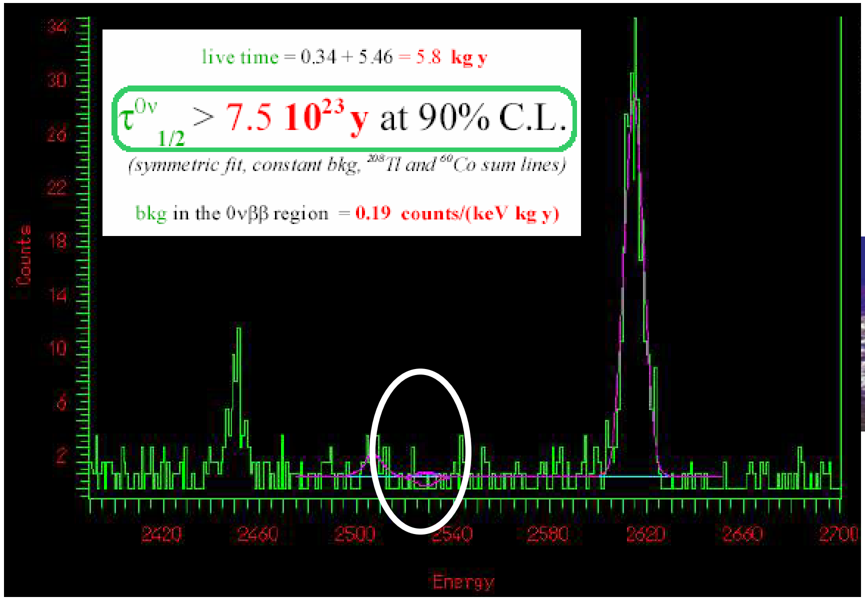
- If the Heidelberg-Moscow ^{76}Ge result is correct, should be confirmed "easily"
- If not, want to push sensitivities to $m_{\beta\beta}^2$ to at least level of δm^2_{23} (*maybe* δm^2_{12})
  – approximately two (*maybe four*) orders of magnitude lower than present situation
- Experiments are very difficult ➔ want confirming signals in multiple isotopes
  – many exciting ideas for future experiments

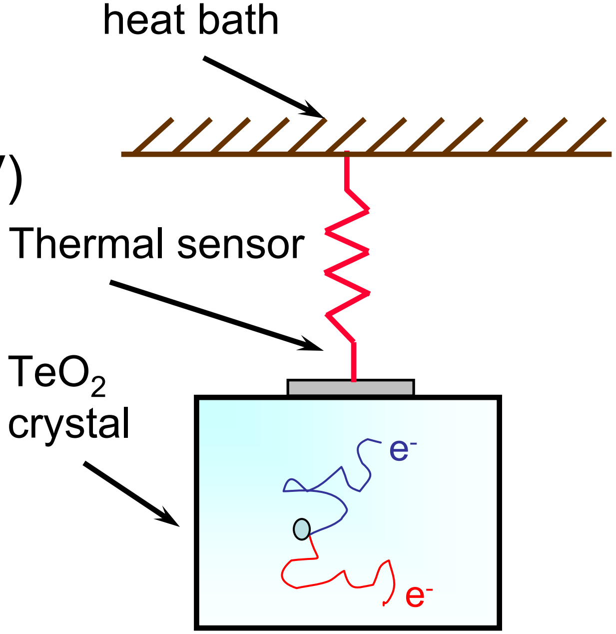
0νββ Approaches: CUORE

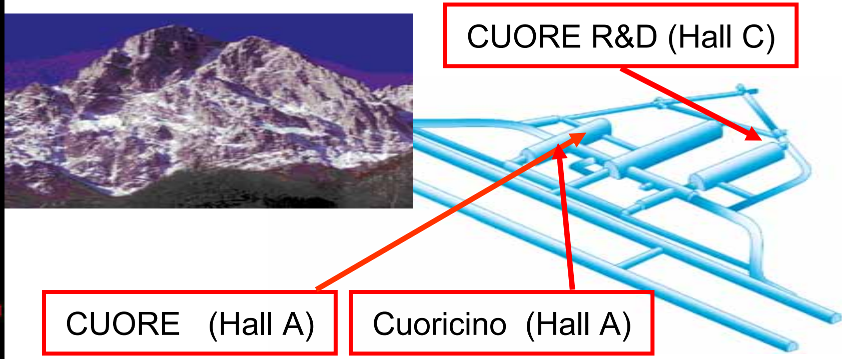
- Calorimetric (thermal) detector which is the ββ source (TeO_2)
  - ~keV resolution at ββ endpoint (2528 keV)
  - Currently running “Cuoricino”, 40 kg
  - Full CUORE expects to have 750 kg, reduced background levels

figures courtesy E.Fiorini



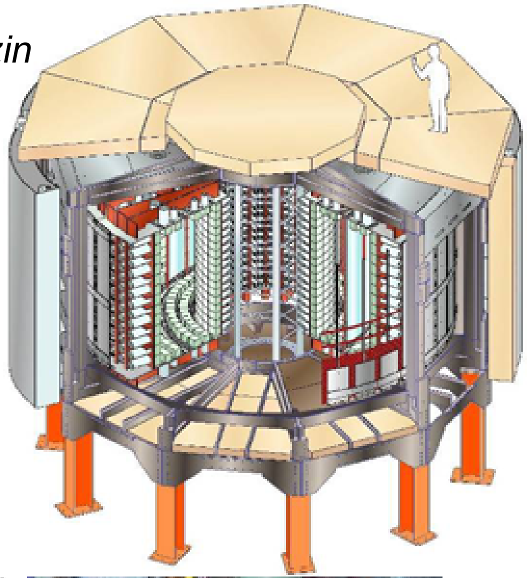




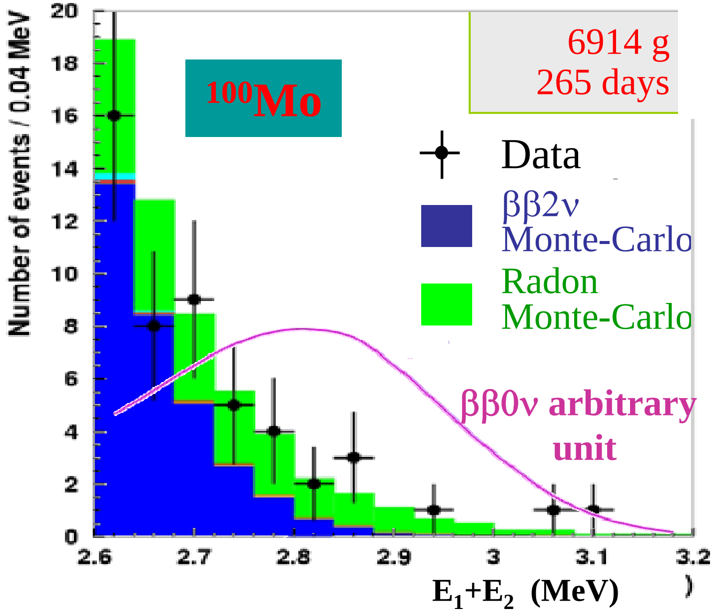


$0\nu\beta\beta$ Approaches: NEMO-3

figures courtesy X.Sarazin



- Tracking/calorimetric detector external to source foils (10kg of $\beta\beta$ isotopes)
  - Geiger mode wire chambers, B=25G
  - Scint/Low Rad. PMT calorimeter
  - Gamma and neutrino shielding
  - First results w/ ^{100}Mo and ^{82}Se
  - Developing proposal to scale to 100kg

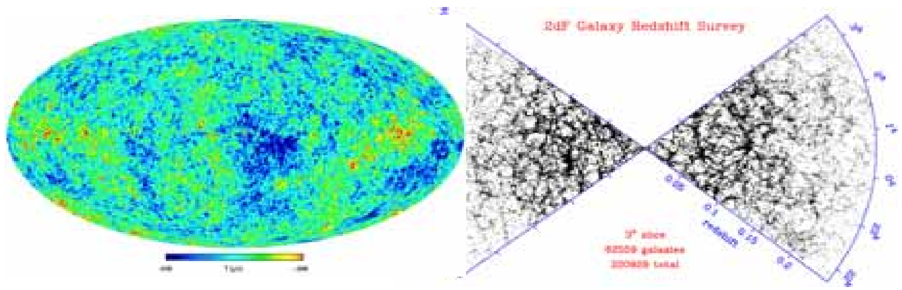


detector in Frejus mine

Other Mass Determinations?

figures courtesy K. Eitel

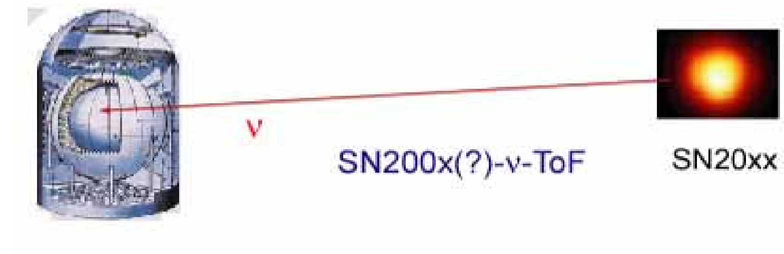
cosmology &
structure formation



D.N. Spergel et al: Σm_ν < 0.69 eV (95%CL)

powerful, but very indirect

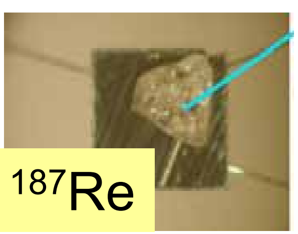
astrophysics:
SN ToF measurements



potential for ~few eV sensitivity

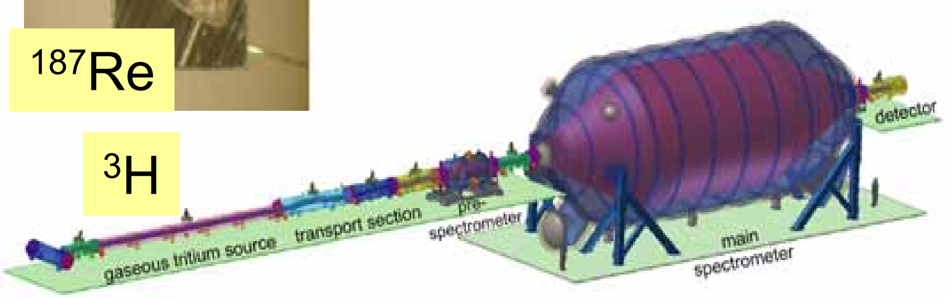
direct, but precision requires detailed knowledge of SN

β decay kinematics: microcalorimeters
magnetically adiabatic collimating electrostatic spectrometers



^{187}Re

^{3}H



direct, but very challenging experiments

KATRIN

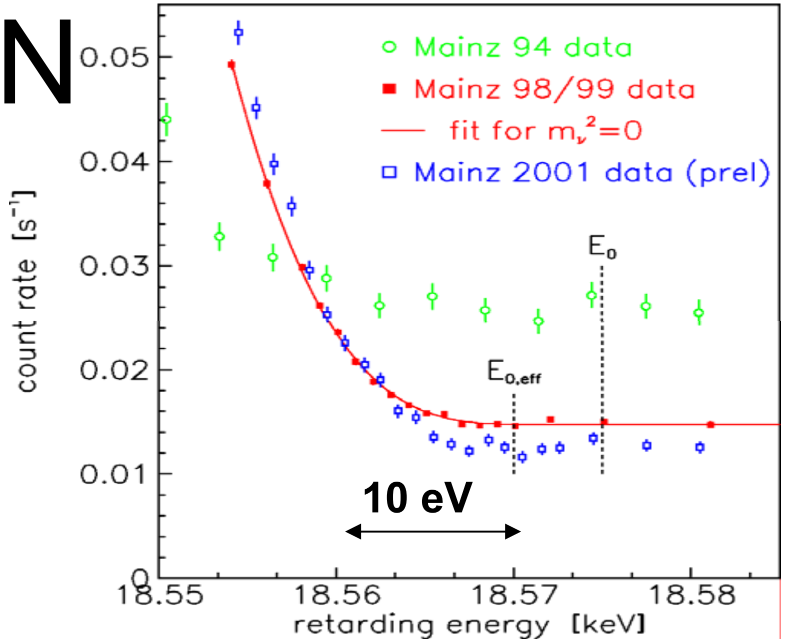
$$^3\mathrm{H} \rightarrow {}^3\mathrm{He} + \beta + \bar{\upsilon}$$

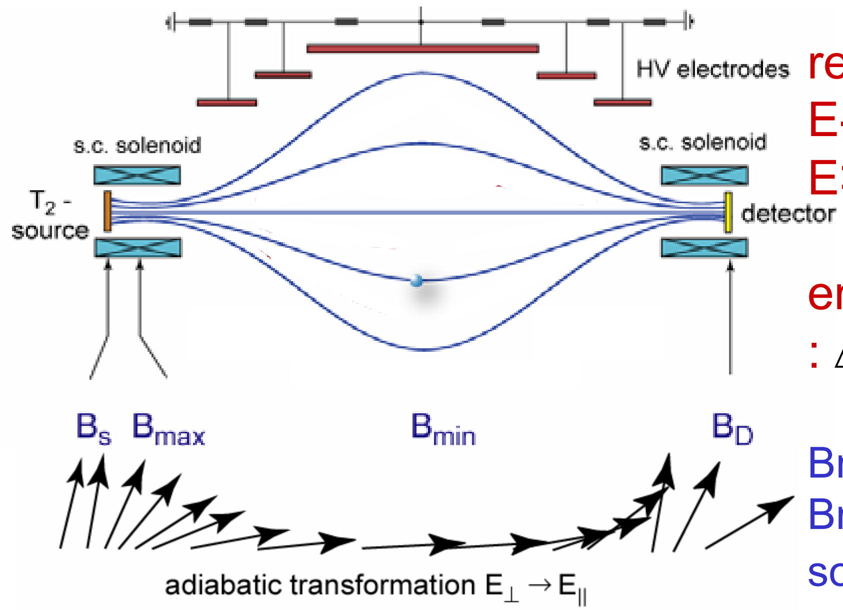
phase space determines energy spectrum

$E_0 = E_e + E_\nu$ (+ recoil corrections)

$$dN/dE \propto (E_0-E_e) \times [\,(E_0-E_e)^2 - m_\nu^2\,]^{1/2}$$

theoretical β spectrum near endpoint





retarding (variable) E-field allows only $E>\Delta E_{ret.}$ to pass

energy resolution: $\Delta E/E=B_{min}/B_{max}$

Bmax = 6 T
Bmin = 3×10-4 T
so ΔE~1 eV

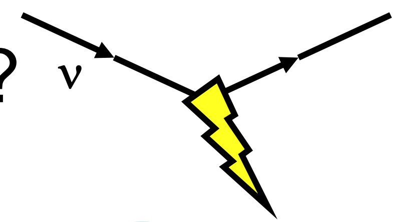
MAC-E spectrometers (Mainz, Troitsk)
m_ν<2.2eV(95%CL)
(sensitivity limit)

KATRIN sensitivity
m_ν<0.2eV(90%CL)
commissioning in 2008

The Broadest Goals

- Understand mixing of neutrinos
  - a non-mixing? CP violation?

- Understand neutrino mass
  - absolute scale and hierarchy
- Understand ν interactions
  - new physics? new properties?



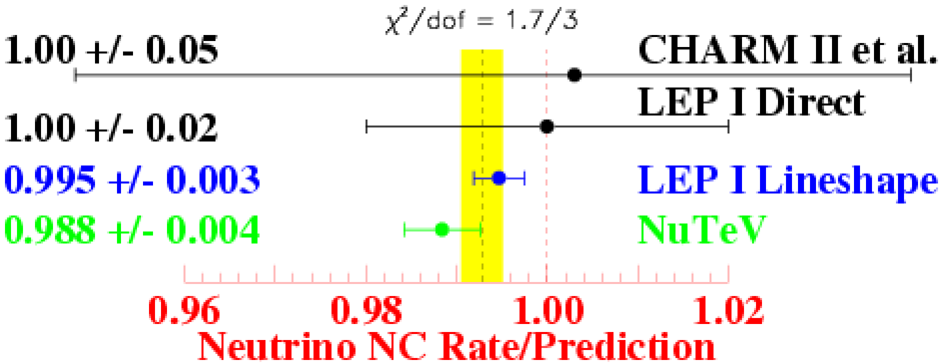
- Use neutrinos as probes
  - nucleon, earth, etc.

Neutrino Interactions

- So broad a subject… so little time
- Precision EWK
- Neutrino magnetic moments
- Parity-violating probe
- (More on non-standard interactions from S. Parke’s talk)

Neutral Currents in Neutrinos

- Neutrino neutral current?
  - LEP invisible width, only 2σ
  - NuTeV may be very large isospin violation

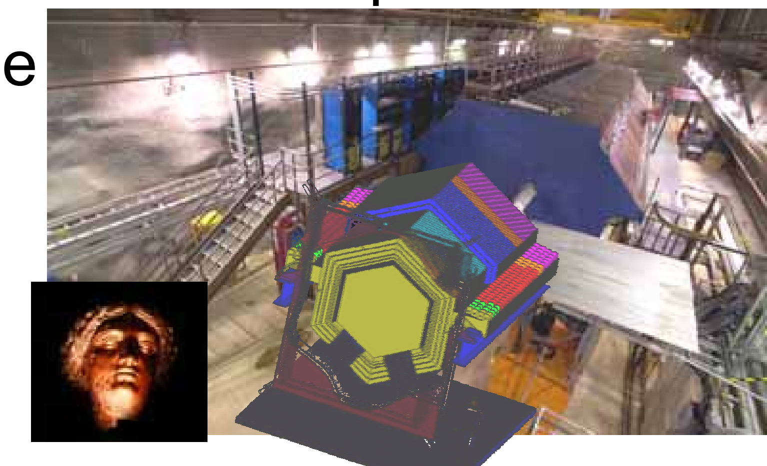


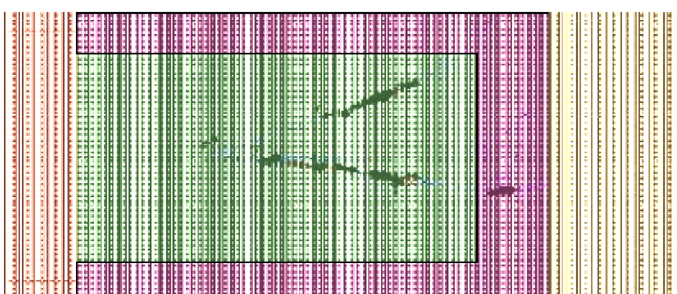
- Future reactors? *Conrad, Link, Shaevitz*
  - if reactor experiments have precision for θ_{13}, may also be able to measure neutral currents
  - opportunity for a purely leptonic probe

$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$$

MINERvA, for Oscillations

- Noted that neutrino interactions are poorly known…
- Backgrounds or signal rate uncertainties for next accelerator oscillation experiments could limit precision
- Enter MINERvA at NuMI beamline
  - newly approved cross-section experiment in NuMI near hall
  - construction start in late 2006; taking data by 2008

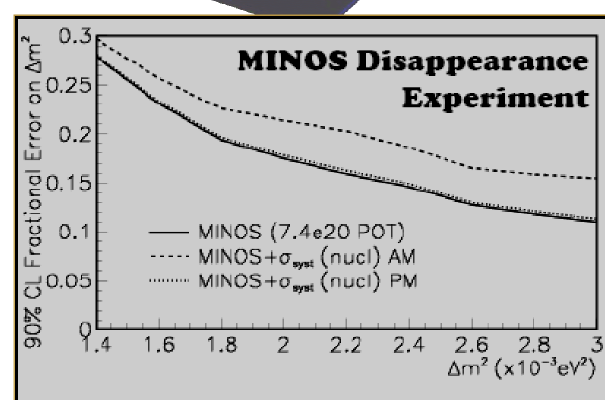




$\nu_\mu p \rightarrow \nu_\mu p \pi^0$
Photon tracks!

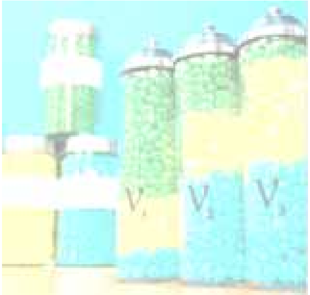
figures courtesy B. Ziemer, D. Harris, R. Flight

For example, MINERvA helps MINOS know relationship between visible and true energy



The Broadest Goals

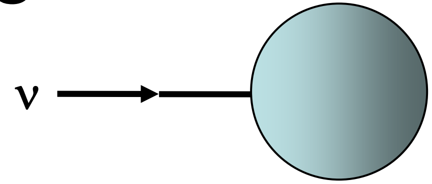
- Understand mixing of neutrinos
  - a non-mixing? CP violation?



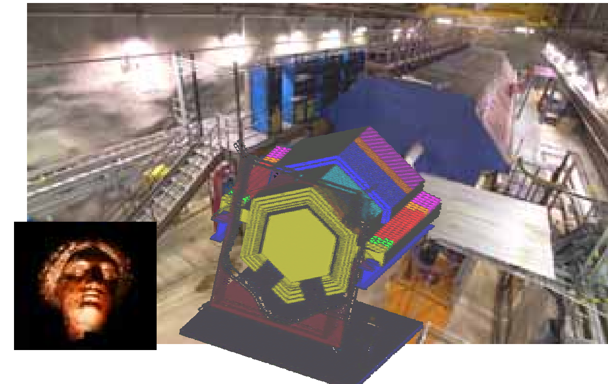
- Understand neutrino mass
  - absolute scale and hierarchy

- Understand ν interactions
  - new physics? new properties?

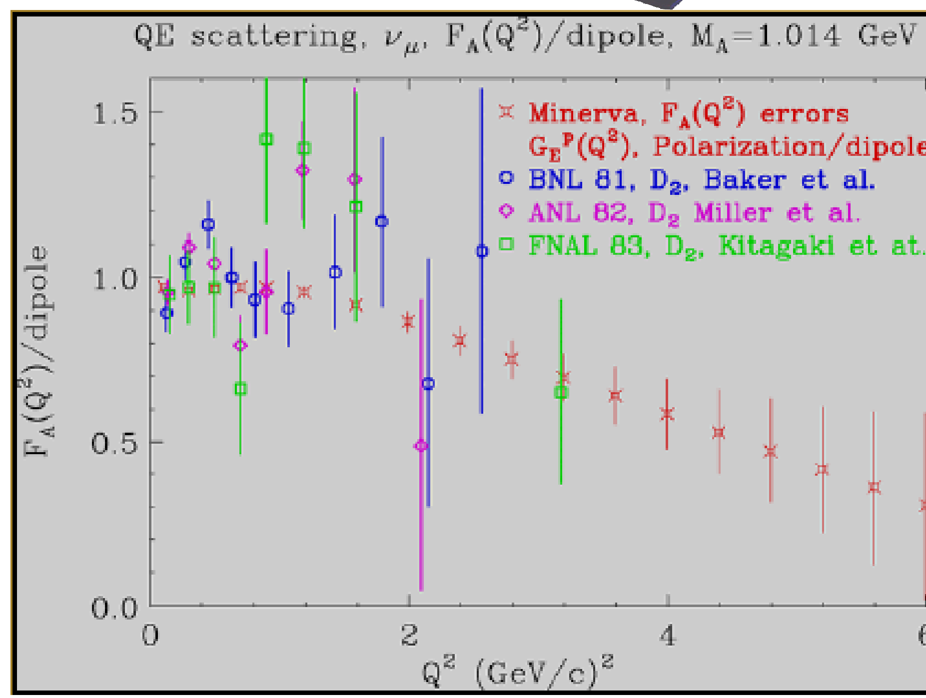
- Use neutrinos as probes
  - nucleon, earth, etc.



MINERvA, Axial Form Factors



- An experiment like MINERvA can add to knowledge of nucleon structure!
  - Jefferson Lab for neutrinos
- Example: axial structure of proton at high Q^2.
  - of interest because of puzzling behavior of vector form factors

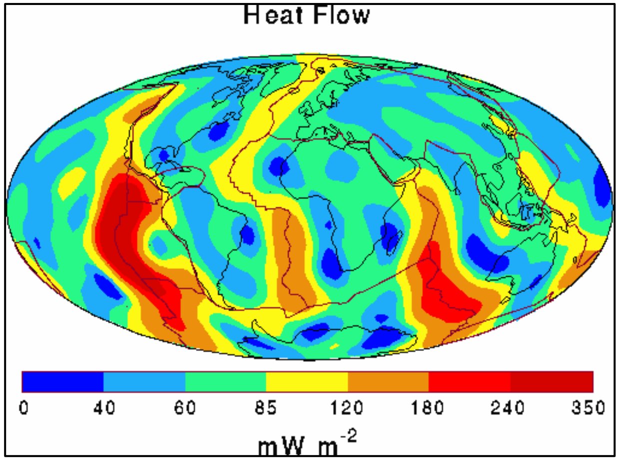


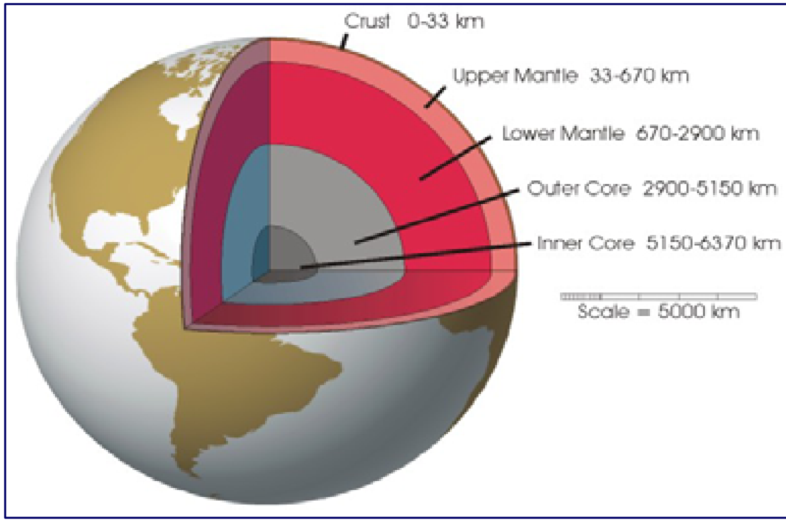
figures courtesy H. Budd, R. Flight

Journey to the Center of the (Spherical) Earth: Geoneutrinos

- Another use of neutrinos as a probe
- The journey in brief:
  - earth radiates 30-45 TWatts in heat
  - the hypothesis: this is due to radioactivity of the earth
  - this radioactivity emits low energy anti-neutrinos from U and Th decays detectable via
    $$\bar{\nu} + p \rightarrow e^{+} + n - 1.8 MeV$$
  - one complication: much of U/Th is in crust

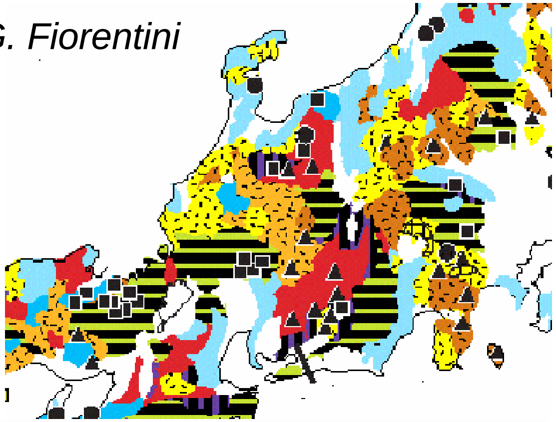
figures courtesy G. Fiorentini



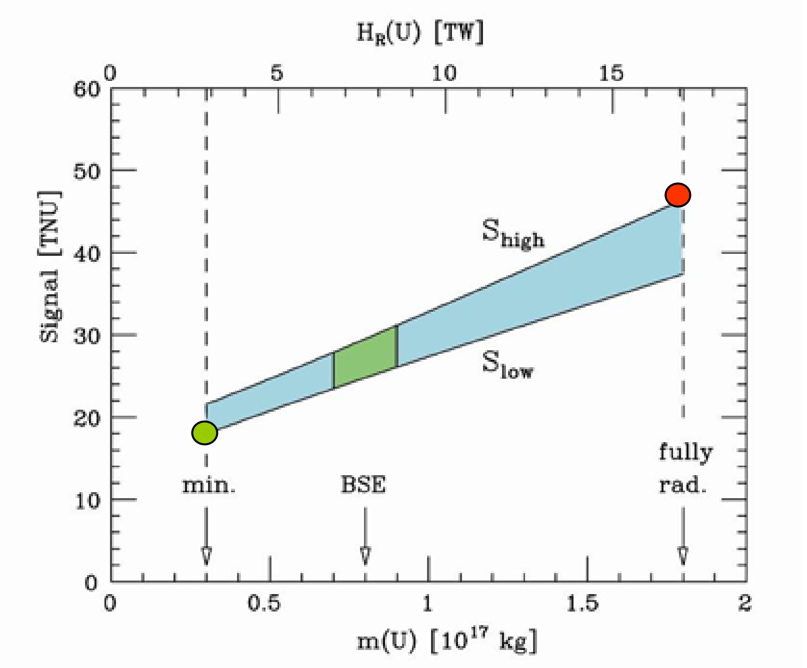


Geoneutrinos (cont'd)

figures courtesy G. Fiorentini



- Crust distribution is location dependent, but can be determined by geochemical surveys
- Subtraction of the variable (local) part leaves the "global" U/Th
- At right, expected local and maximum "global" signal for U
  - "TNU" unit is 10^{-32} ev/prot-yr



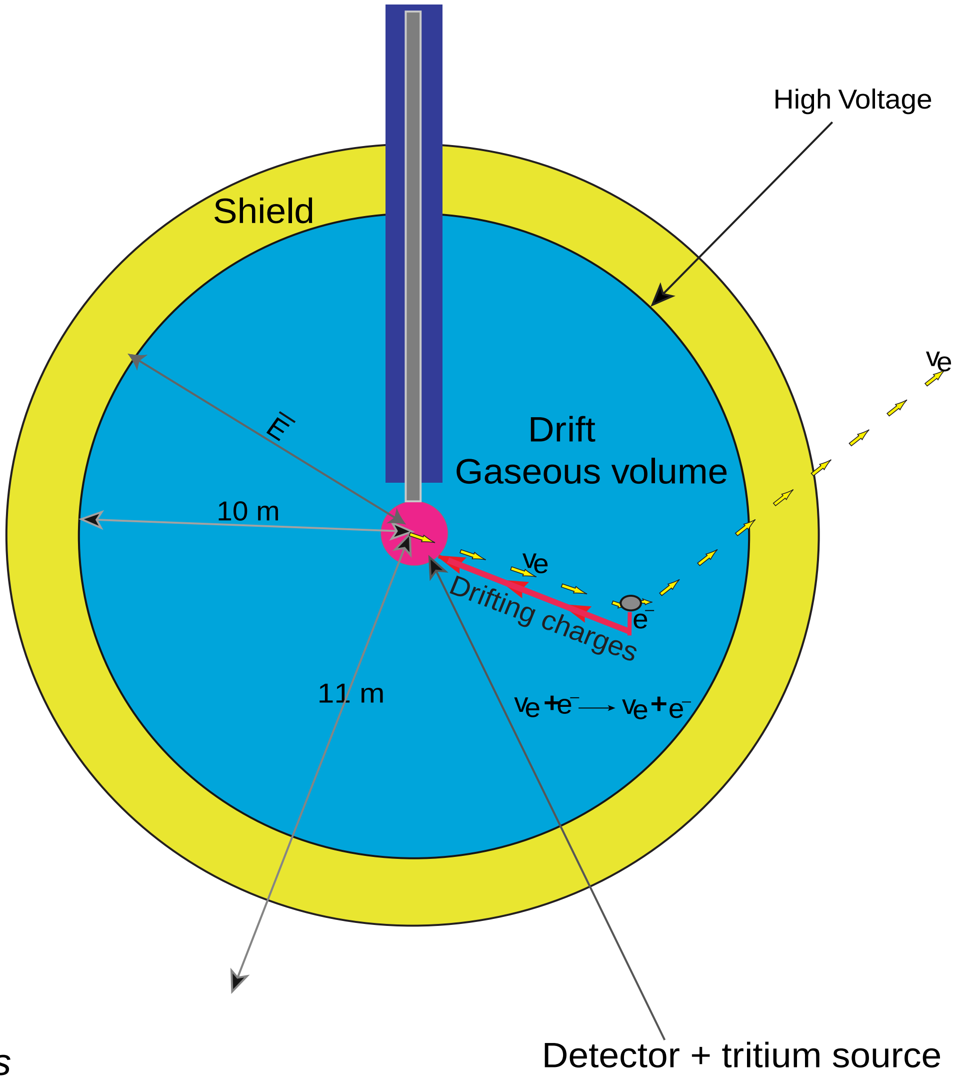
KamLAND S(U+Th)=(82±52stat.) TNU clearly needs more data!

Other Interesting Ideas

- Why is this so important to neutrino physics?
- Field has been driven by unexpected results from nearly every window we've looked in!
- To me, it seems like every neutrino conference I go to I hear at least one novel and audacious idea for an experiment…
  - Gallium source calibration
  - EXO Barium tagging
  - etc.
- *So here's one I recently learned about. It may work, it may not. It is illustrative…*

keV Neutrino Source

- If one could make:
  - 200 MCurie $^3H_2$ source
  - 3000 m^3 spherical Xe TPC volume at 1bar
- One could look at atmospheric L/E in the lab
- NOSTOS experiment. Obviously not trivial technically…



figures courtesy I. Giomataris

Breathless Conclusions

- There is a lot going on in neutrino physics!
- Nature has been kind to us so far, and answers to fundamental questions may be ripe for the picking

- But, new experiments are getting more difficult…
  – Still, we've been historically patient in neutrino physics (e.g., 30 years from Pauli to Reines and Cowan)
  – And it's been worth the wait!

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